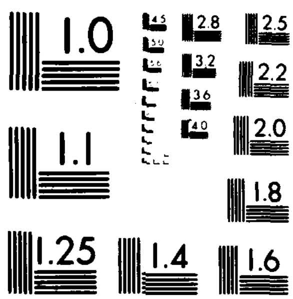
AD-A107 303 DEFENSE COMMUNICATIONS ENGINEERING CENTER RESTON VA F/G 17/2.1
APPLICATION OF DIGITAL TROPOSCATTER TO THE DCS.(U)
SEP 80 J L OSTERHOLZ, W J CYBROWSKI
UNCLASSIFIED DCEC-TR-10-80 NL

1 of 2
AD A
107303



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

LEVEL II

TR 10-80

DEFENSE COMMUNICATIONS ENGINEERING CENTER

AD A107303

TECHNICAL REPORT NO. 10-80

APPLICATION OF DIGITAL TROPOSCATTER TO THE DCS

SEPTEMBER 1980

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

UNCLASSIFIED September 1980

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 14 DCEC-TR 10-80	2. GOVT ACCESSION NO.: AD-A107 303
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): 6 Application of Digital Troposcatter to the DCS	5. TYPE OF REPORT & PERIOD COVERED: 9 Technical Report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): 10 J. L. Osterholz; W. J. Cybrowski	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Defense Communications Engineering Center, Transmission Engineering Division, R200, 1860 Wiehle Ave., Reston, VA 22090	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: N/A
11. CONTROLLING OFFICE NAME AND ADDRESS: Same as #9	12. REPORT DATE: 11 September 80
	13. NUMBER OF PAGES: 12 148
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): N/A	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

A. Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18. SUPPLEMENTARY NOTES

Review relevance 5 years from submission date.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Digital Troposcatter Requirements
Digital Troposcatter Transmission
Multichannel
Provisional Design Criteria
Troposcatter Technology Review

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A DCS digital troposcatter requirements and technology baseline is presented for use by system planners and managers. The current troposcatter link inventory is reviewed to identify those links most likely to be digitized and retained through the 1990's. Current developments in digital troposcatter technology are reviewed, including the results of key tests. Provisional design criteria which were developed for digital troposcatter links based on this testing are presented. This report supersedes draft DCEC TR 17-76, "Integration of Digital Troposcatter into the Defense Communications System"

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

409629

and draft DCEC TR 9-79, "Application of Digital Troposcatter to the DCS".

Accession For		
NTIS GRA&I	X	
DTIC TAB	☐	
Unannounced	☐	
Justification		
By		
Distribution/		
Availability Codes		
Dist	Avail and/or Special	
A		

TECHNICAL REPORT NO. 10-80

APPLICATION OF DIGITAL

TROPOSCATTER TO THE DCS

SEPTEMBER 1980

Prepared by:

J. L. Osterholz
W. J. Cybrowski

Technical Content Approved:

FREDERICK L. MAYBAUM
Lt Col, USAF
Chief, Transmission
Engineering Division

Approved for Release:

ROBERT E. LYONS
Deputy Director

FOREWORD

The Defense Communications Engineering Center Technical Reports (TR's) are published to inform interested members of the defense community regarding technical activities of the Center, completed and in progress. They are intended to stimulate thinking, encourage information exchange, and provide guidance for related planning and research. They are not an integral part of the DoD PPBS cycle and should not be interpreted as a source of program guidance.

Comments or technical inquiries concerning this document are welcome, and should be directed to:

Director
Defense Communications Engineering Center
1860 Wiehle Avenue
Reston, Virginia 22090

EXECUTIVE SUMMARY

This Technical Report presents DCS digital troposcatter requirements and a technology baseline. It also provides system planners and managers with the results of key system decisions to assist in the detailed system planning of DCS digital transmission projects involving troposcatter.

Troposcatter has historically provided a major long-haul, multichannel transmission capability for the Defense Communications System (DCS). This capability was established via extensive tandem systems such as 486L, which stretches from Spain to Turkey; the North Atlantic Radio System (NARS), which connects the North American continent and Europe via Canada, Greenland, Iceland and the United Kingdom (UK); the Japan Troposcatter System (JTS) which provides multichannel connectivity between Okinawa and Mainland Japan; and the European Tropo-Army (ETA),which provides multichannel connectivity between the Federal Republic of Germany (FRG) and the UK. The subsequent development of a global military communications satellite system, the Defense Satellite Communications System (DSCS), and the emergence of many foreign national communications systems (e.g., in Japan and FRG) has provided the stimulus to reassess the need for troposcatter transmission in a modern, digital DCS, particularly in view of the escalating costs of maintaining equipment based on essentially 20-year-old technology.

It is on this basis that the current troposcatter link inventory of the DCS is reviewed. Using economic and operation guidelines, a subset of this inventory is identified representing those links which are likely to be retained and digitized in the DCS through the 1990's. As expected, a significant reduction in numerical requirements is forecast, with approximately 30 percent (about 40 links) of the current inventory making up the candidate digital troposcatter link requirements model. Deactivation of those links not included in this subset is generally predicated on the availability of other connectivity or a potential reduction in subscriber requirements (to permit cost effective use of lease service), and will not be specifically addressed.

With this in mind, subsystem design requirements are identified for a DCS digital troposcatter transmission capability which can meet the overall DCS design requirements of performance, availability, and digital system compatibility. For example, the capability to modify certain DCS inventory analog troposcatter radios to permit interface with a digital troposcatter modem is defined, as well as subsystem performance requirements for new troposcatter RF facilities. Much of the current DCS troposcatter equipment is approaching 20 years of age and is becomming increasingly difficult to support logistically, and therefore replacement RF components must be identified to satisfy those link requirements where digitization of the in-place troposcatter radio equipment is impractical.

Given a selective but significant digital troposcatter requirement and the desirability of developing alternative digital transmission technologies, two RDT&E programs were conducted by the MILDEPS, one by the Army and one by the Air Force, to address development of a megabit digital troposcatter transmission capability. As a result of these efforts, digital troposcatter transmission has been successfully demonstrated over a number of actual links at nominal data rates up to 12.6 Mb/s. One of these modem techniques, the Distortion Adaptive Receiver (DAR), developed by the Air Force, is being used in the TRI-TAC AN/TRC-170( )(V) tactical digital troposcatter radio terminal full scale development program. Another modem technique, the Adaptive Decision Feedback Equalizer (ADFE), was developed under an Army DCS RDT&E program. The ADFE technique implementation resulted in the MD-918/GRC modem which the Army and Air Force plan to use for upgrading the first two DCS Digital European Backbone (DEB) links. The RDT&E phase for these two modem techniques has been completed. Combined U.S. and NATO system level comparative testing of the two modem techniques over links of the NATO ACE High transmission system have been accomplished. Since the specialized nature of these technologies has precluded their widespread visibility, this report compares the current developments by means of a review of digital troposcatter technology, a comparison of key test results, and an examination of implementation practicalities.

Based on the performance data obtained during the aforementioned testing, provisional design criteria have been developed for DCS digital troposcatter links and are presented herein. This report provides the analysis and derivation of these criteria which have previously been stated in DCEC TR 12-76 [1]. The criteria described utilize new system performance parameters, such as fade outage rate and duration, which are more intimately related to the performance of current and anticipated DCS subscriber services than any used heretofore. These criteria are intended to be used in all DCS digital troposcatter link implementations. Links operating in the diffraction and mixed propogation modes are also required to meet the performance critieria.

Following this analysis, a number of transmission system engineering issues are examined to address certain key system engineering decisions such as required spectrum availability and the extent to which the AN/TRC-170 can be used in the DCS, as well as the viability of using transmission components (e.g., time division multiplexers) which have not been specifically optimized for troposcatter use. Some of these areas remain open because the full impact of a particular issue has not been defined (e.g., the lack of available spectrum in the 1 and 2 GHz frequency bands). Nevertheless, the current baseline digital troposcatter capability is seen to adequately support near term implementations such as the Digital European Backbone (DEB) transmission upgrade, see Figure 1.

Finally, appendicies are included in this report which address areas of special interest; i.e., the derivation of a digital troposcatter channel performance model, digital troposcatter link acceptance and quality assurance (QA) methods, and a digital troposcatter modem performance specification. The QA appendix complements a similar section in DCEC TR 12-76 which deals with digital Line-of-Sight (LOS) link acceptance and quality assurance. The modem performance specification represents the technical basis for the planned DCS digital troposcatter modem procurement.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF TABLES

I. THE ROLE OF TROPOSCATTER IN THE DCS

1. NETWORK PHILOSOPHY

Troposcatter transmission as employed in the Defense Communications System (DCS) has historically provided multichannel communications to subscriber communities which, because of geographic or political constraints, are relatively isolated from the rest of the network. As an example, troposcatter transmission currently provides backbone connectivity in some regions of the DCS in order to join multichannel subscribers which are dispersed beyond line-of-sight (e.g., the 486L and JTS Systems). Troposcatter transmission experienced its greatest expansion between 1958 and 1968 in this application. Unfortunately, requirements for rapid connectivity coupled with a lack of realistic implementation guidelines resulted in the notoriously erratic performance of many troposcatter links installed during this time [2]. Sparse refurbishment programs compounded the substandard performance of these links and further reduced the effectiveness of troposcatter as a backbone communications medium. This undoubtedly contributed to the present categorization of troposcatter as an extraordinary maintenance burden and the belief that troposcatter is intrinsically undesirable for cost effective, multichannel communications.

The development of operational military satellite communications (MILSATCOM) systems, such as the Defense Satellite Communications System (DSCS), provides an alternative multichannel transmission capability beyond microwave line-of-sight (LOS), and thus reliance on the troposcatter medium is expected to be reduced, particularly in long tandem applications. However, it is generally agreed that the most effective transmission network will continue to employ a mixed media inventory (i.e., satellite, LOS, troposcatter, leased service) where political, economic, survivability, and performance (i.e., system availability) considerations determine the selection of one transmission medium over another to satisfy a particular requirement. The current development of digital transmission technology provides a convenient point to readdress the area of transmission media utilization in the DCS and to define the specific role, if any, for troposcatter.

Generally, multichannel communications over very long distances are most effectively provided by communications satellites. However, a number of situations require government-owned connectivity where terrestrial communications, in general (troposcatter in particular), can be considered as preferred alternatives over MILSATCOM. These situations (identified in Table I and based on the planned MILSATCOM capability for the 1980-1985 time frame), do not generally represent viable satellite applications. It can be shown that terrestrial transmission (particularly troposcatter) is generally preferred over the present DSCS system for moderate cross section multichannel connectivity requirements spanning 500 miles (800 km) or less. Further, it is clear that exclusive use of communications satellite trunking will not result in an optimally survivable network due to the dependence on one or, at best, a small number of nodal equipments (e.g., the DSCS space segment) for connectivity. Thus, due primarily to cost and survivability considerations, troposcatter transmission is likely to be utilized in the DCS for the foreseeable future.

TABLE I. GENERIC TROPOSCATTER TRANSMISSION APPLICATIONS

- o PROVIDE CONNECTIVITY TO MODERATELY DISPERSED (100-400 mi, 160-650 km) MULTICHANNEL SUBSCRIBER COMMUNITIES.
- o EXTEND DCS MULTICHANNEL CONNECTIVITY TO ISOLATED SUBSCRIBERS.
- o PROVIDE COST EFFECTIVE TERRESTRIAL ALTERNATE ROUTING BETWEEN EARTH SATELLITE TERMINALS WHERE LOS IS INFEASIBLE OR PARTICULARLY VULNERABLE.
- o PROVIDE AN "EXTENDED RANGE" JMTSS-TYPE RESTORAL CAPABILITY.

A review of the present DCS transmission network, in light of the guidelines summarized in Table I, resulted in the identification of troposcatter links which are likely to be retained in the post-1980 DCS. From this set of candidate links, which represent on the order of 30 percent of the current DCS troposcatter inventory, certain links have been selected for near term digitization and, where appropriate, refurbishment as part of larger transmission upgrade projects such as the Digital European Backbone (DEB). Detailed descriptions of these projects are found in the DCS System Improvement Plan (SIP) 1-75, DCS Five Year Plan (FYP) 78-82, the DCS FYP 79-83, DCS FYP 80-84, DCS FYP 81-85 and DCS FYP 82-86. A brief overview describing the scope of both near term and future projected DCS digital troposcatter requirements is presented in the following subsections.

2. TROPOSCATTER UPGRADES - NEAR TERM

a. Digital European Backbone (DEB). Five troposcatter links have been selected for digitization and upgrade as part of the DEB project. Digitization of link T0607 (Bocksberg-Berlin), and the digitization of LOS feeder links from Feldberg north to Bocksberg will provide:

- o Alternative DCS multichannel and widespread digital service to major U.S. force commanders.

- A diverse digital terrestrial route for certain dedicated Berlin wideband requirements.

- Enhanced security for Berlin and Northern Germany communications through implementation of bulk encryption.

Additionally, it is planned that the cross channel link T0111 (Hoek Van Holland - Martlesham Heath) will be digitized and upgraded. One end of this link will be moved from Hoek Van Holland to another site in the Netherlands in order to serve users more effectively and increase survivability in the North European Area. Specific benefits of the retention and digitization of link T0111 are:

- Provide bulk encrypted capacity to serve increased user requirements resulting from a major Headquarters relocation.

- Enrich connectivity to combat units to be deployed in Belgium, the Netherlands and Luxemburg.

- Enable the increased use of allied communications systems (e.g., UK STARRNET) by providing an interconnect at Martlesham Heath, UK.

Also included under the DEB project is the digitization of links T0055, T0056, and T0057 in Italy to provide digital communications to USN and USAF units stationed in the Naples, Sardinia, and San Vito areas. Troposcatter links to be upgraded under the DEB program are shown geographically in Figures 1, 2 and 3.

b. Digital Terrestrial Extension - Turkey and Greece. This project was approved in FYP 78-82 (but not funded) and will initiate the refurbishment and digitization of the DCS transmission system within Turkey. The DCS transmission system in Turkey serves a widely dispersed multichannel subscriber community. Links T0060, T0263, and T0250 have been initially selected for upgrade through equipment replacement and digitization. The completion of the Terrestrial Extension - Turkey project was approved in DCS FYP 79-82, and is illustrated in Figure 2. This transmission upgrade will permit the extension of digital terrestrial service in Turkey, provide a digital terrestrial altroute between DSCS facilities for selected DCS subscribers, and provide terrestrial connectivity between DSCS terminals in Turkey. Similarly, digitization of Link T0227 in Greece will provide diverse routing to Europe and CONUS by permitting access to alternate DSCS facilities in Greece.

3. TROPOSCATTER UPGRADES - FUTURE

Future digital troposcatter implementations will be keyed to the balanced, cost effective utilization of available transmission media and the disposition of U.S. forces worldwide. Table II provides a summary of likely future digital troposcatter requirements based on subscriber requirements projections.

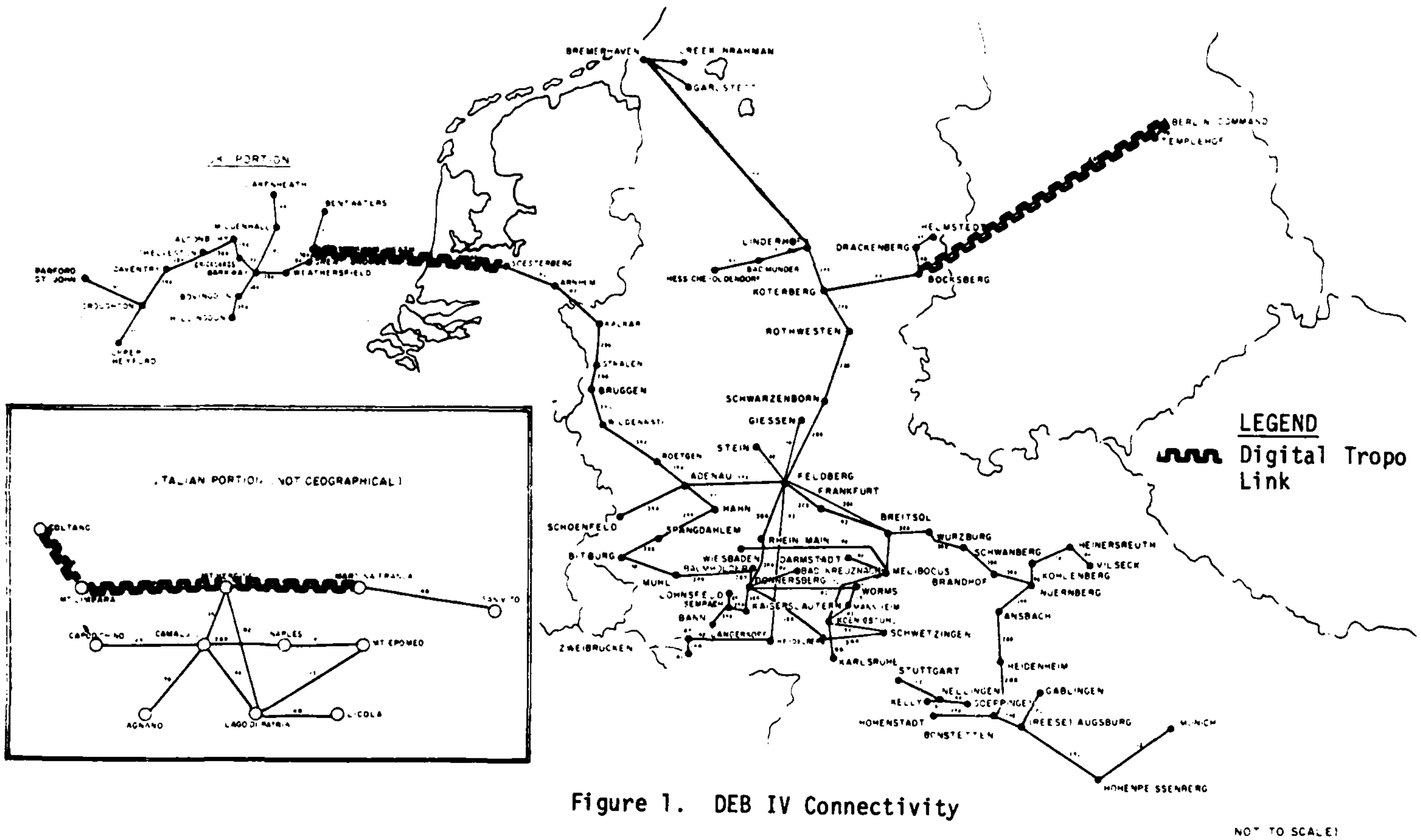


Figure 1. DEB IV Connectivity

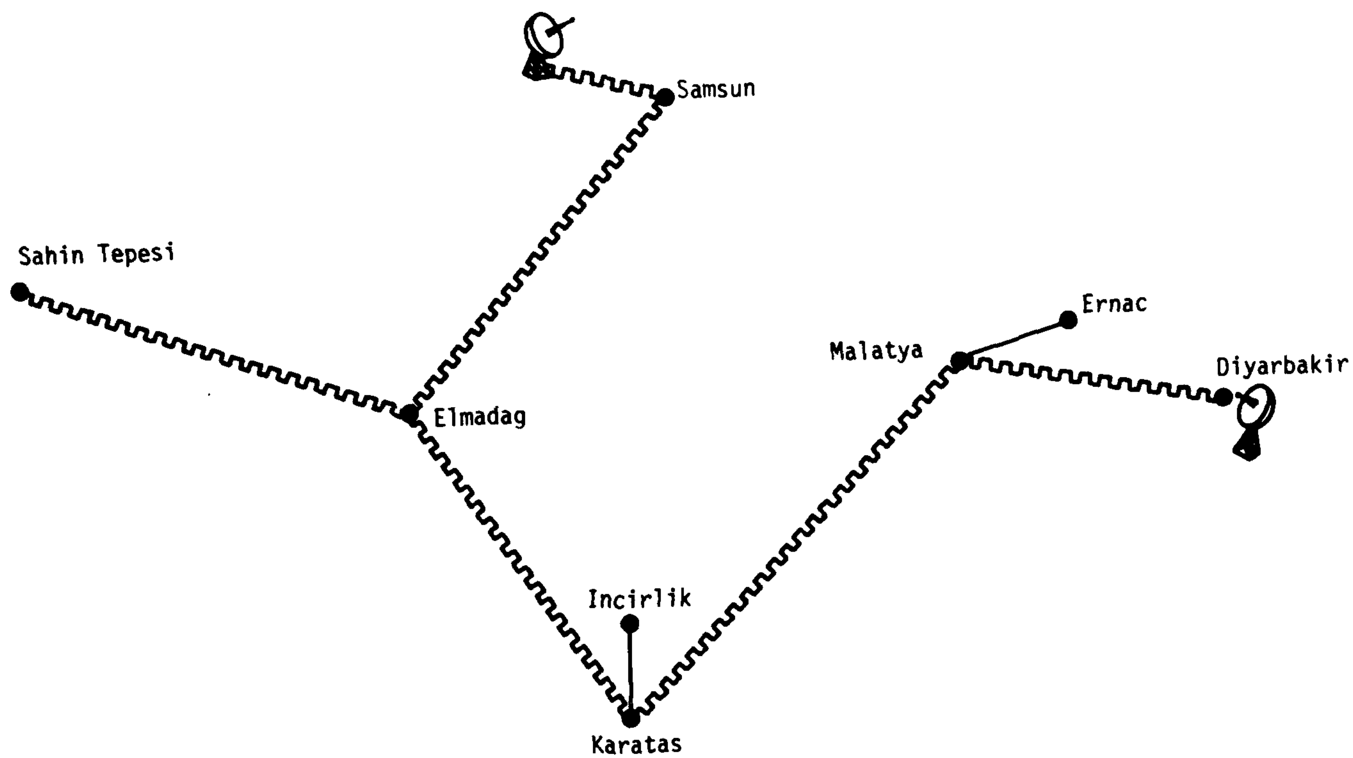


Figure 2. Digital Terrestrial Extension - Turkey

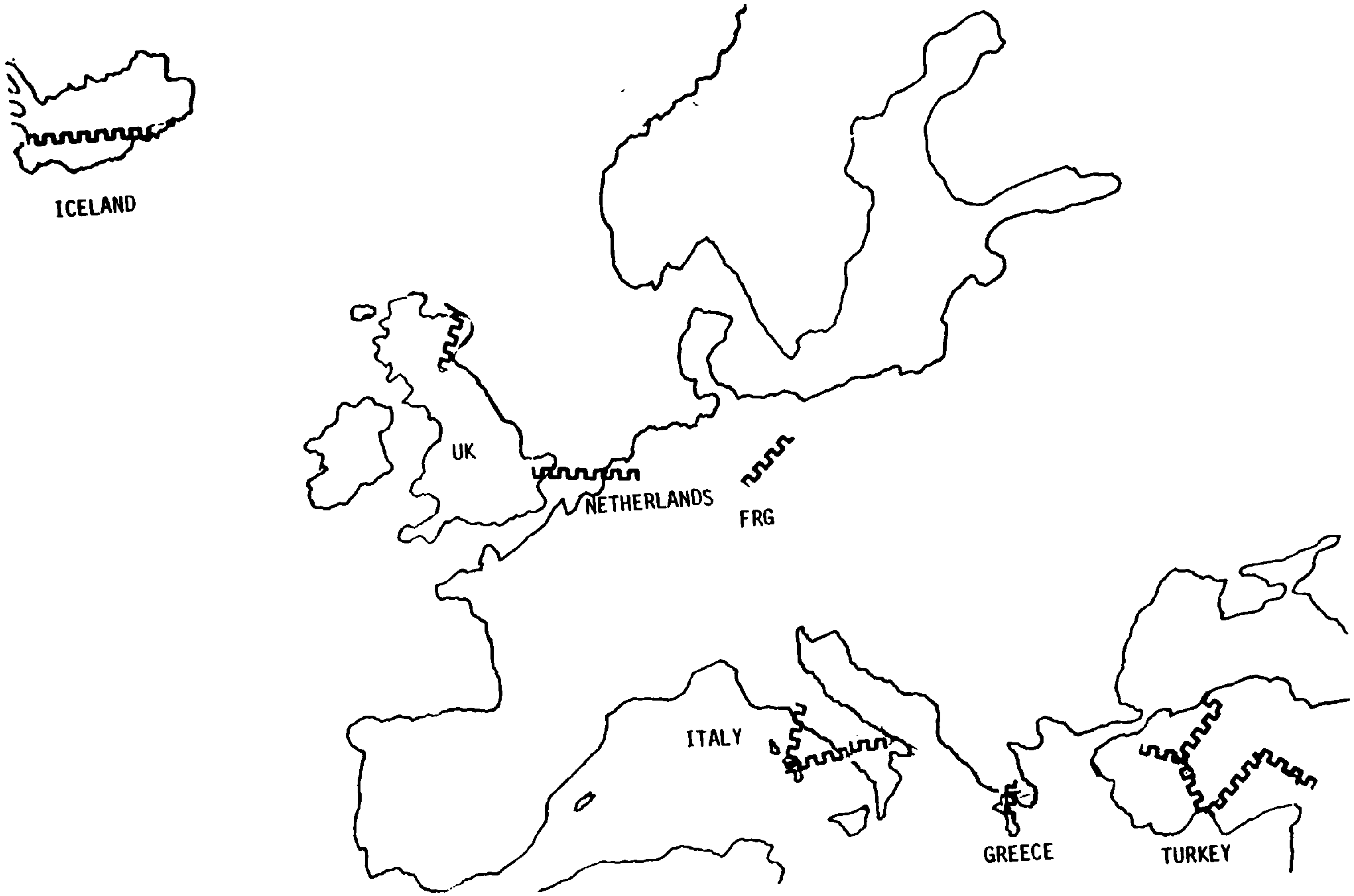


Figure 3. Candidate DCS Digital Tropo Links in Europe.

The Arctic Backbone Digitization Project, listed in Table II, is envisioned to utilize DSCS assets (or alternative commercial satellite facilities) in conjunction with terrestrial media to provide enhanced and more reliable connectivity for isolated subscribers presently serviced by the western links of the North Atlantic Radio System (NARS), and possibly by eastern portions of the Dew Line (White Alice) Troposcatter System in Canada. The ultimate extent of upgrade programs in the Arctic and Canadian regions is dependent on the retention or upgrade of the Dew and Pine Tree Early Warning Systems and the desirability of using commercial leased transmission facilities to supplement available government facilities.

A decision to implement digital troposcatter in the Japan Area (e.g., the Japan Troposcatter System or JTS) will follow an evaluation of requirements for maintaining a U.S. Government-owned transmission plant in Japan. The JTS is presently maintained via contract with Japanese private industry (e.g., Nippon Electric Company) and has been implemented with predominantly Japanese equipment. If continued U.S. Government ownership of transmission facilities within Japan and Okinawa is affirmed and digitization is implemented, then specialized digital troposcatter modems (unavailable in Japan) may have to be supplied by the U.S.

TABLE II. PROJECTED FUTURE DCS DIGITAL TROPOSCATTER IMPLEMENTATIONS

- o DIGITAL TERRESTRIAL EXTENSION - GREECE
- o ARCTIC BACKBONE DIGITIZATION (SATELLITE/TROPO UPGRADE TO SUPPORT ISOLATED SUBSCRIBERS)
- o JAPAN AREA DIGITIZATION

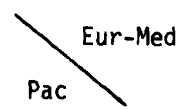
Table III provides, for the European/Mediterranean and Pacific areas, a summary distribution of candidate troposcatter links catagorized by link length and cross section. Table III also includes the portions of potential Arctic and Canadian troposcatter requirements which serve Iceland and Greenland, and provide alternate CONUS-Europe connectivity. It is noted from Table III that planned and projected requirements of up to 9.6 Mb/s must be accommodated. As a further aid in visualizing potential DCS troposcatter requirements, Figures 3 and 4 indicate the geographical locations of those DCS troposcatter links which appear in Table III (except for those links located in the Artic area).

TABLE III. DCS CANDIDATE DIGITAL TROPO REQUIREMENT MATRIX

Path Length

Cross Section (equiv. VF channels)	≤ 240(km) ≤ 150(mi)	240-320(km) 151-200(mi)	321-400(km) 201-250(mi)	401-480(km) 251-300(mi)	< 480(km) < 300(mi)	Cross Section (Mb/s)
≤ 24	8 /	2 /	1 /	1 /	0 /	
> 24 ≤ 48	0 / 0	0 / 0	0 / 0	[illegible] / 0	0 / 0	3.232
> 48 ≤ 96	3 / 2	5 / 2	4 / 2	1 / 0	3 / 1	6.464
> 96 ≤ 144	4 / 1	10 / 0	0 / 0	0 / 0	0 / 0	9.696

Key



* Includes selected Arctic Area Links

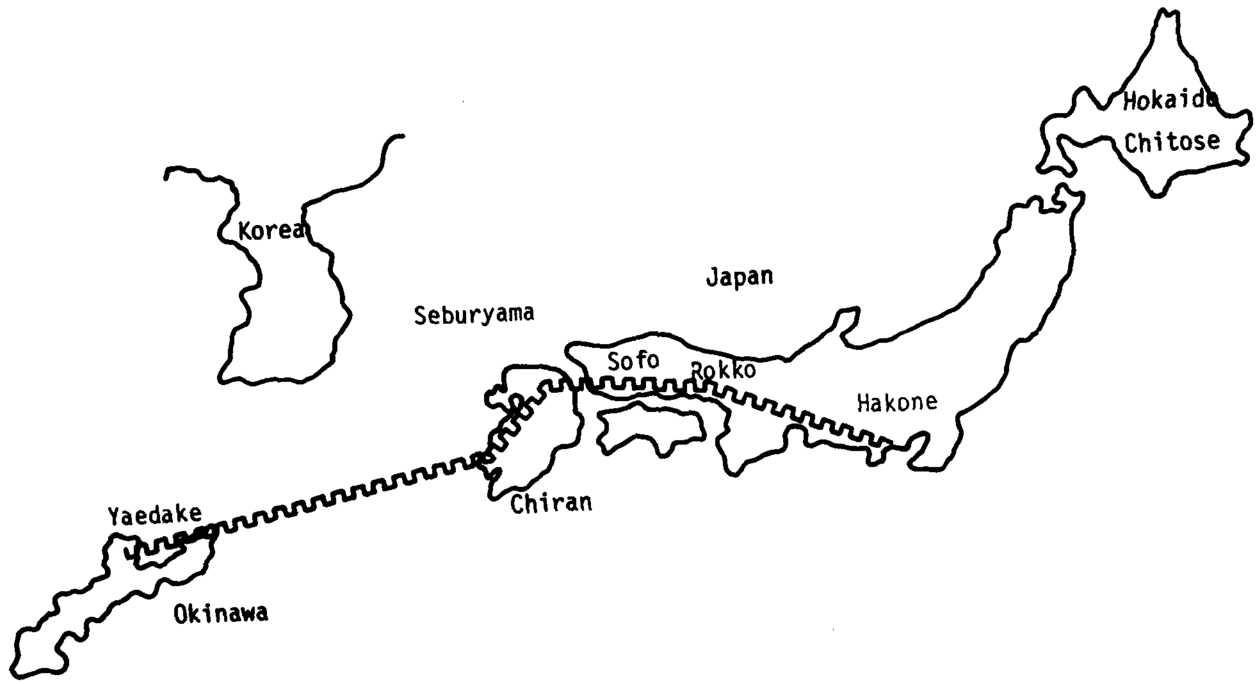


Figure 4. Candidate DCS Digital Troposcatter Links in the Pacific

II. DCS DIGITAL TROPOSCATTER TRANSMISSION CONFIGURATIONS

The initial implementations of digital troposcatter in the DCS are likely to be within an asynchronous, pulse stuffing transmission network. As with the DCS digital LOS radio, AN/FRC-(170)(V) series, the digital troposcatter signal processing function and its attendant RF transmission components (collectively defined as the digital troposcatter facility) must provide certain standard subsystem capabilities. With the exception of a reduced link cross section (expected to be less than 10 Mb/s because of bandwidth allocations), the digital troposcatter transmission facility should provide the same flexibility as other DCS digital transmission facilities. Thus, the digital troposcatter transmission facility should be capable of operation with the following DCS digital equipments:

- AN/FCC-99 - Time Division Multiplexer
- KG-81 - Bulk Encryption Device
- AN/GSC-24 - Time Division Multiplexer
- Service Channel Multiplex or SCM (3 channel configuration of the AN/FCC-98)
- Low Speed Time Division Multiplexer (LSTDM).

To enhance the flexibility of digital troposcatter in branching repeater and dropped channel applications, the capability must be provided to combine synchronously one or two parallel data inputs or Mission Bit Streams (MBS) from the DCS digital equipments with a single 192 kb/s Service Channel Bit Stream (SCBS) as shown in Figure 5. In order to assure the synchronous combining of these inputs, it will also be necessary, at least in initial implementations, to provide transmit clock and receive timing to the multiplex (or cryptographic) equipment as shown in Figures 6a and 6b. Specific digital interface specifications for the equipment listed above can be found in DCEC TR 12-76, [1].

As noted in Figure 5, the troposcatter RF transmission facility must accommodate aggregate data rates of 3.424 Mb/s, 6.656 Mb/s, or 9.888 Mb/s. The final output bit rate must be transmitted efficiently and within the data rate/transmitted bandwidth requirements listed in Table IV. Achievement of these spectrum efficiencies may be especially difficult for digital troposcatter which trades bandwidth for performance. However, achievement of these objectives will clearly facilitate the acceptance of digital troposcatter allocations, particularly within congested areas of nations, where DCS facilities share the same frequency bands as PTT facilities, television broadcasting service and navigation aids.

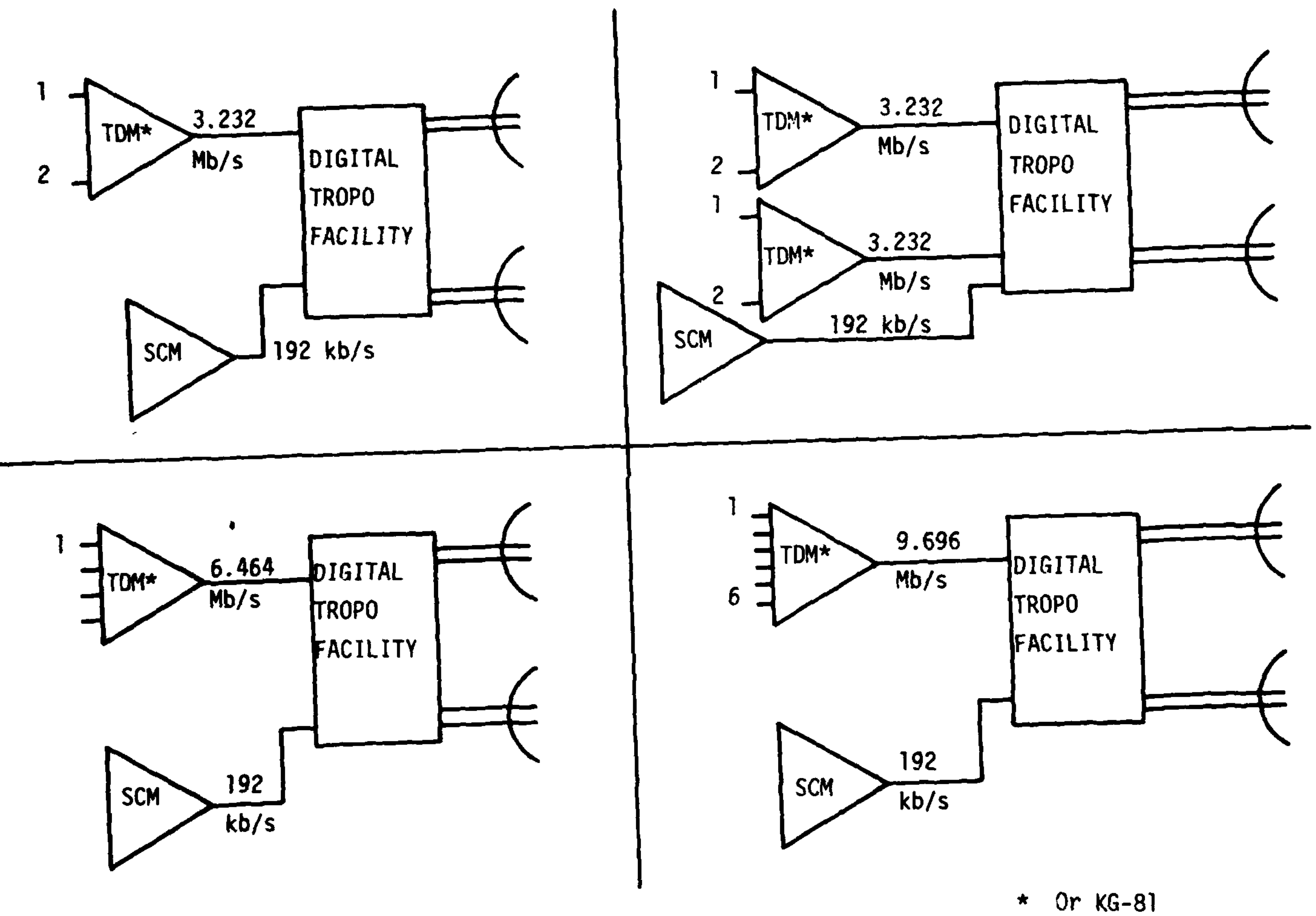


Figure 5. DCS Digital Troposcatter Configurations

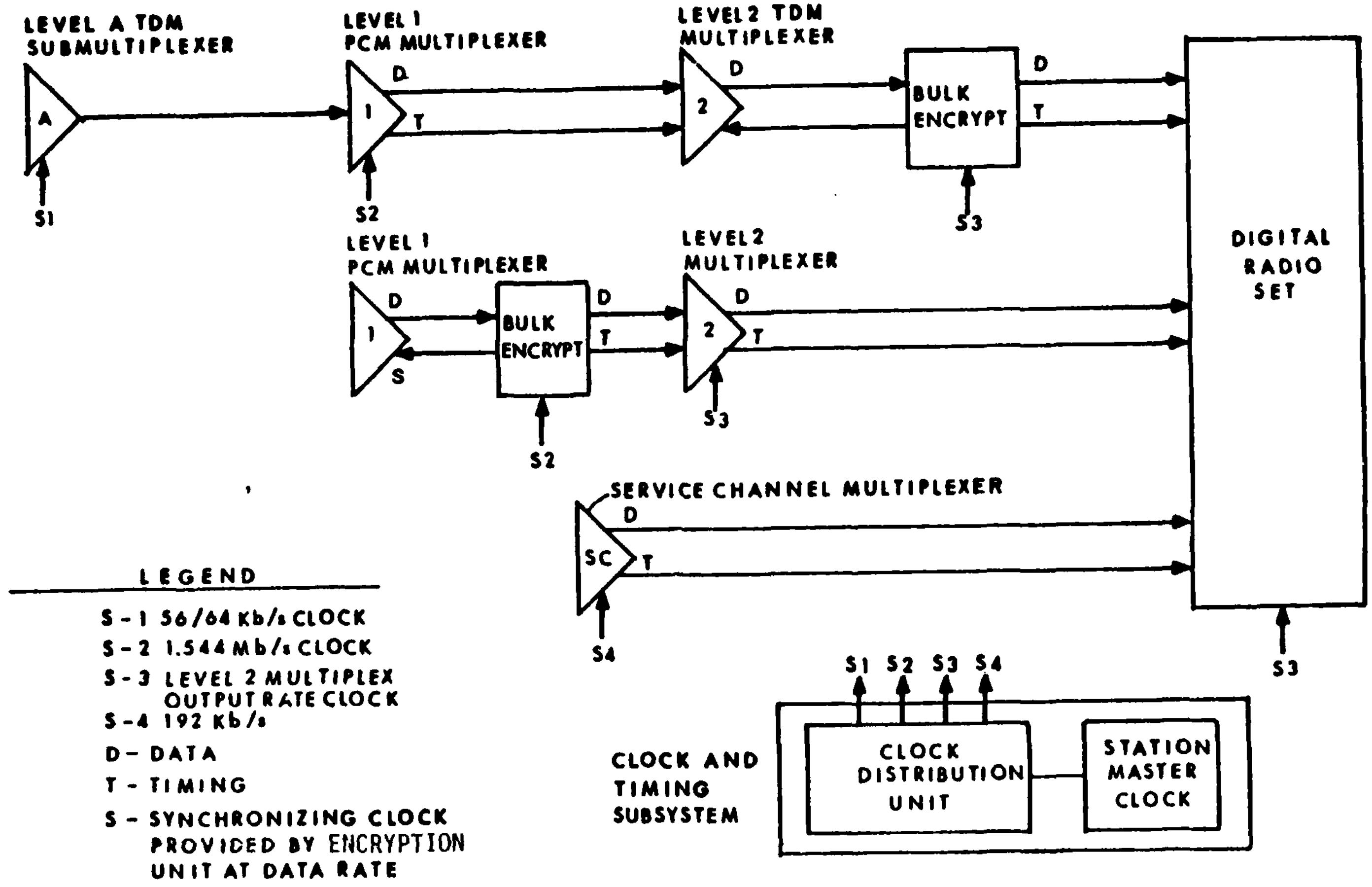


Figure 6a. Digital Tropo System Data/Timing Flow (Transmit)

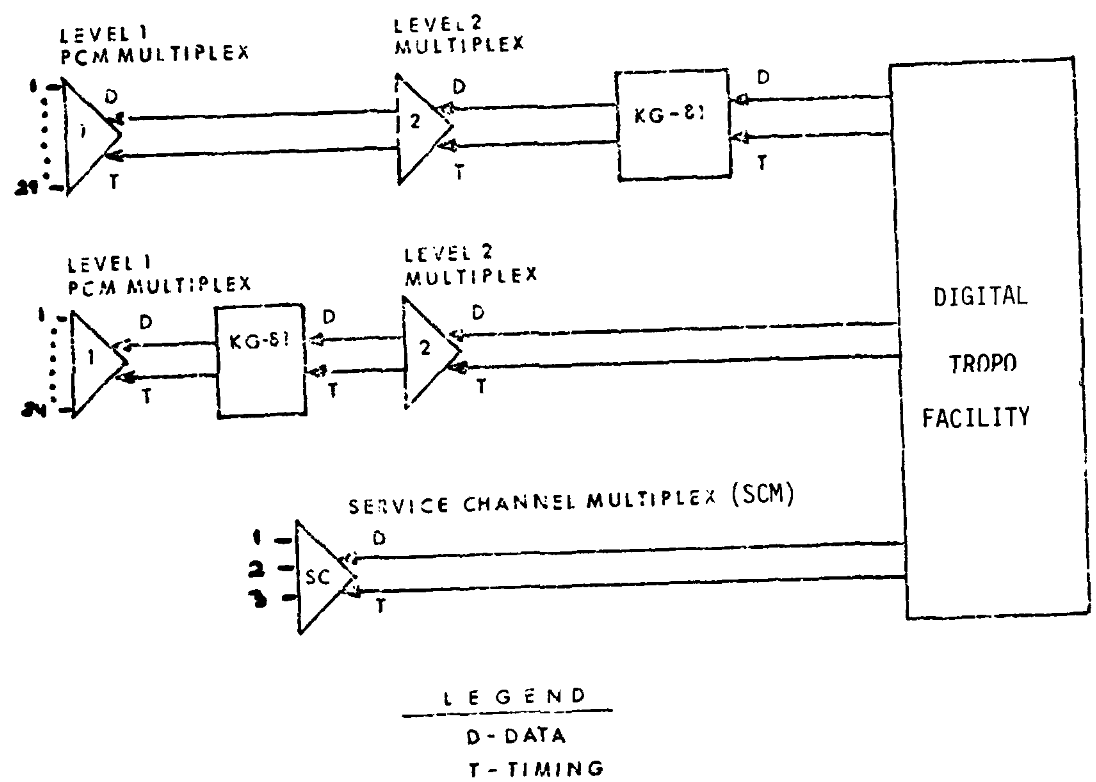


Figure 6b. Digital Tropo System Data/Timing Flow (Receive)

TABLE IV. DCS DIGITAL TROPOSCATTER SPECTRAL EFFICIENCY OBJECTIVES

TOTAL TRANSMIT RATE*(Mb/s)	SYSTEM BANDWIDTH OBJECTIVE**(MHz)
9.888	7.0
6.656	7.0
3.424	3.5

* (sum of MBS and SCBS bit rates but excluding modem TDM overhead)
**per diversity frequency

The essential system requirement for diversity transmission also contributes strongly to the pressure for high spectrum efficiency. Diversity transmission is required for troposcatter in order to enhance performance during fading. Multiple transmission paths are provided in diversity transmission under the assumption that fading will occur nearly independently in each path and thus at least one path will be above threshold nearly all of the time. In the DCS, any of a number of diversity configurations may be implemented as required by the propagation characteristics of a particular link. These configurations are illustrated in Figure 7. As shown in Figure 7, quad diversity transmission (i.e., four independent channels) is often provided by using dual frequency diversity in conjunction with dual space diversity. This configuration is called space/frequency diversity. Space/frequency diversity is generally accepted to be the most effective, but it unfortunately requires the most bandwidth. For each link implemented in space/frequency diversity, four separate frequency allocations must be obtained. Since the acquisition of four wideband (7-10 MHz) allocations is expected to be the exception rather than the rule, the use of alternate diversity configurations such as "space/polarization" (actually quad space diversity) or space/ angle diversity is expected to become more prevalent than space/frequency diversity.

The application of angle diversity to augment dual space diversity links and thereby to approximate quad diversity performance without additional frequency allocations is also possible and is, as noted above, very likely to be used in the DCS. The convergence of space/angle diversity performance on space/frequency diversity performance (i.e., true quad diversity) is a function of the cross-correlation between individual angle diversity received signals (i.e., scattered energy received from separate portions of the tropospheric scatter volume via angularly separated feeds) and thus is related to the operating frequency and antenna beamwidth.

For the lower frequency L-Band (755-985 MHz) links, unless large antennas are used, considerable correlation between angle diversity receiver outputs can be expected because the wider antenna beamwidths will result in largely overlapping angle diversity scatter volumes. Thus, the diversity improvement

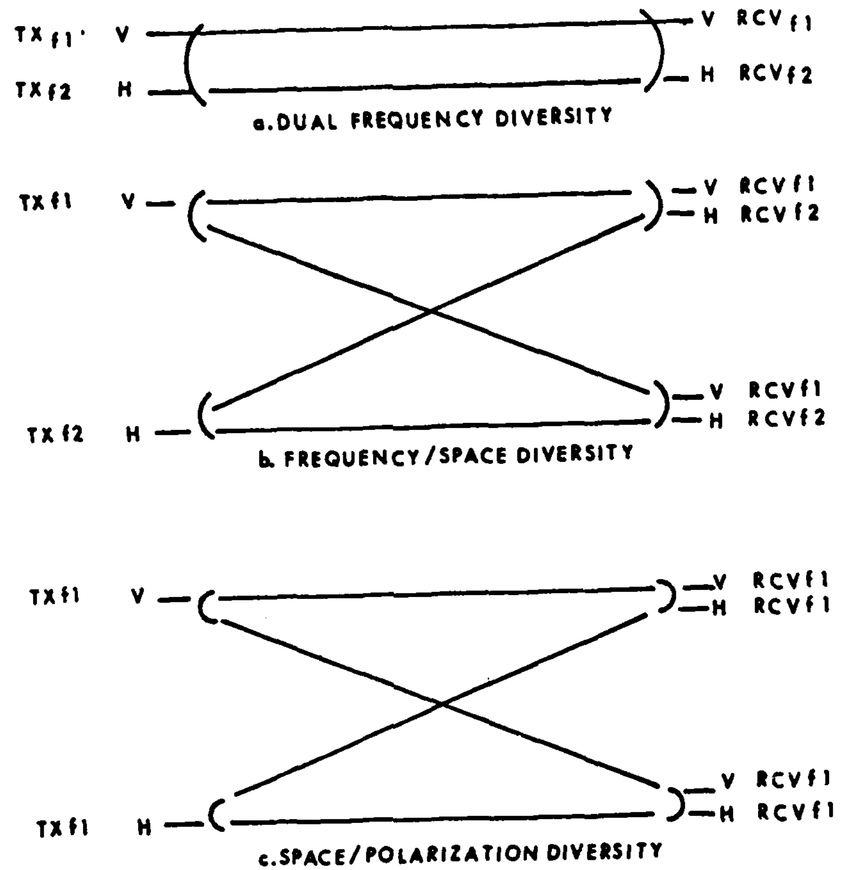


Figure 7. Tropo Diversity Configurations

attributable to angle diversity will probably be only equivalent to quad space or "polarization" diversity. For the higher frequency C-Band troposcatter systems, lower cross correlation between angle diversity receiver outputs is expected due to a greater confinement of angle diversity scattering volumes resulting from narrower antenna beamwidths. Thus for medium distance C-Band links, the performance of space/angle diversity can be expected to approximate ideal quad diversity more favorably. For most DCS troposcatter links which are expected to require continued use of the lower frequency bands, the use of angle diversity will likely be restricted to converting existing marginal quad diversity systems to eighth order (space, frequency, and angle) or as a replacement for frequency diversity on DCS links with 60 foot (18 meter) and larger antennas. As a rule of thumb, angle diversity will be useful for links with an antenna beamwidth to scatter angle ratio of 0.875 or less.

The most important component of the digital troposcatter facility is the signal processing electronics; that is, the electronics used for modulation, diversity combining, demodulation, and detection. This function will be implemented as a modem (developed under government sponsorship) and integrated with the RF equipment necessary to provide a complete transmission capability, such as IF/RF converters, high power amplifiers, and low noise receivers. Only a digital troposcatter modem rather than a complete digital troposcatter terminal was developed because (1) DCS troposcatter link requirements are relatively few in number and (2) The majority of DCS troposcatter frequency allocations vary over three bands from L Band (UHF) to C Band (tactical SHF), depending on the path length and the area of deployment as indicated in Table V.

TABLE V. DCS TROPOSCATTER FREQUENCY BANDS

BAND (MHZ)	GEOGRAPHICAL REGION
300-400	ARCTIC (one link)
755-985	TURKEY, ARCTIC
1700-2700	ITALY, TURKEY, GREECE, WEST PAC, UK
4400-5000	FEDERAL REPUBLIC OF GERMANY (FRG)

Based on these observations, the full scale RDT&E development of more than the specialized signal processing function is not cost effective. Furthermore, it was observed that this function could be made compatible with both the transfer characteristics of in-place analog troposcatter radios of recent manufacture and those of commercially available RF components. Thus, the procurement of a digital troposcatter modem for the DCS is currently planned. This modem will be compatible with the inventory radios listed in Table VI and the transfer characteristics of commercially available up and down frequency converters. Utilization of this approach will permit the digitization of servicable, in-place analog troposcatter facilities, possible utilization of TRI-TAC radio RF assets, and the cost effective digitization of troposcatter facilities where RF equipment must be replaced and the TRI-TAC RF equipment can be used.

TABLE VI. MAJOR DCS INVENTORY TROPOSCATTER RADIO EQUIPMENTS AND CONFIGURATIONS SUITABLE FOR DIGITIZATION

RADIO/CONFIGURATION	FREQUENCY BAND
AN/FRC-39A(V) AN/FRC-123 AN/MRC-85 AN/MRC-98 AN/MRC-113 AN/FRC-102	755-985 MHz
AN/FRC-56	1.7-2.4 GHz
AN/FRC-96 AN/FRC-97	2.55-2.7 GHz
AN/TRC-132, 132A	4.4-5.0 GHz

Figure 8 illustrates the interface between the radios listed in Table VI and the DCS digital troposcatter modem. As most of the equipments listed in Table VI are pre-1970 vintage, it is recognized that certain minor modifications will be required to permit conversion of these radios to digital operation. Although a detailed list of modifications has not yet been compiled for all radios, a fairly complete understanding of the required functional modifications exists. These modifications are summarized in Table VII.

TABLE VII. TYPICAL ANALOG TROPOSCATTER RADIO MODIFICATIONS

FUNCTION	MODIFICATION
RF/IF CONVERSION CIRCUITRY	STABILIZE LOCAL OSCILLATOR CHAINS TO AT LEAST 1 x 10(-9) (SHORT TERM)
IF CIRCUITRY	PROVIDE WIDEBAND ($\geq$ 10 MHz) 70 MHz DIVERSITY INPUT/OUTPUTS PRIOR TO AUTOMATIC GAIN CONTROL CIRCUITRY (AGC)
IF INTERFACE	50 OHMS, UNBALANCED XMT LEVEL: -4 to +16 dBm RCV LEVEL: -10 TO -75 dBm

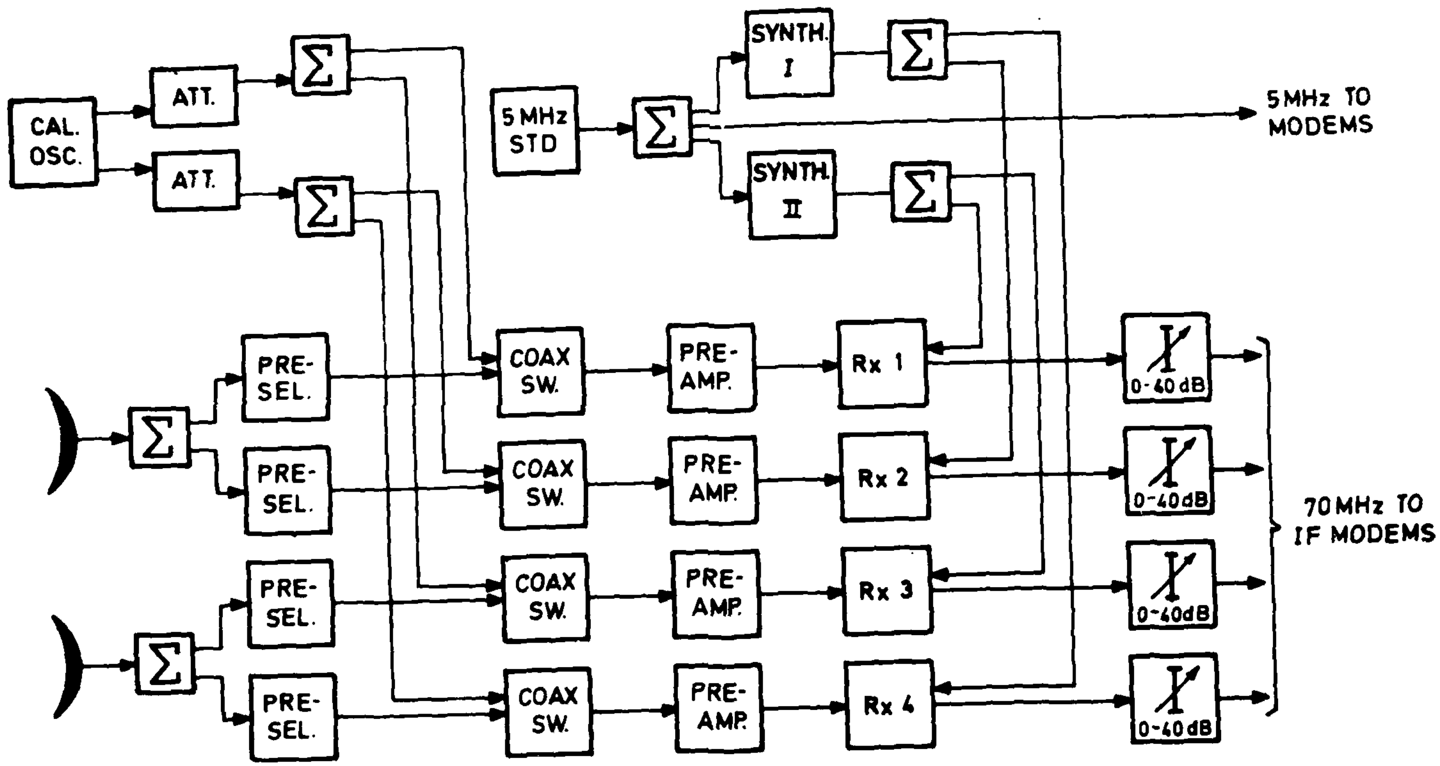
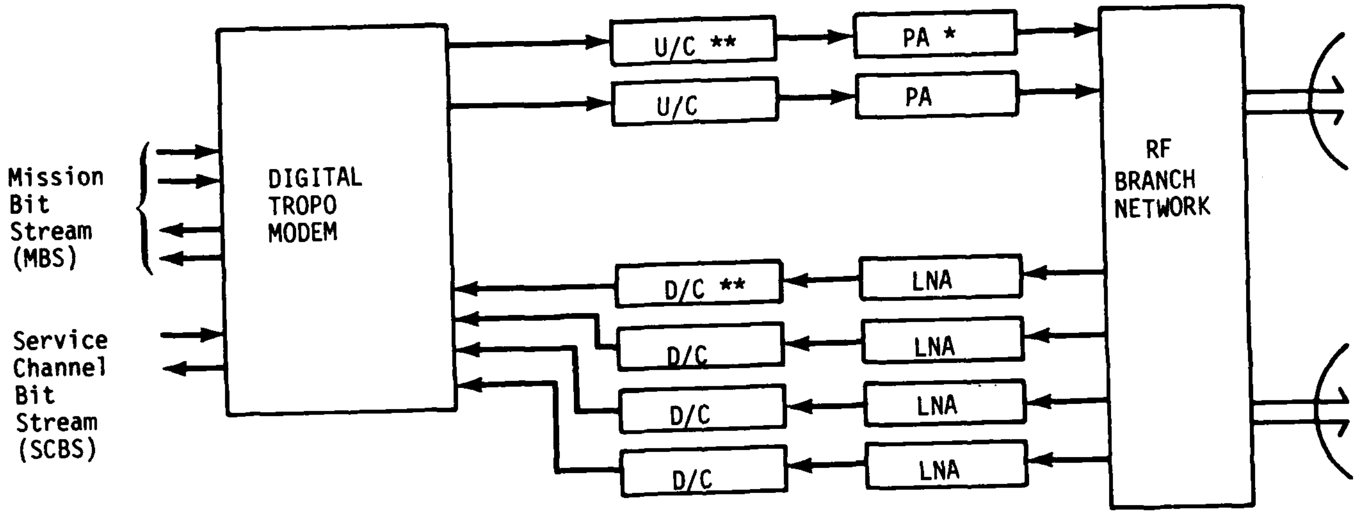


Figure 8. Typical Digital Tropo Facility (Analog Radio Configuration) (Shown For Space/Frequency Diversity) Receiver Configuration

Since large portions of the present DCS analog troposcatter inventory (e.g., AN/GRC-66, AN/FRC-75) are technologically obsolete and relatively costly to maintain, thought must also be given to the specification and acquisition of RF components to refurbish troposcatter links using these aged radios (e.g., in the Digital Terrestrial Upgrade - Turkey). Fortunately, only certain new RF components are required, since all signal processing and digital system interfaces can be provided by the troposcatter modem itself. Figure 9 illustrates those major RF components which, together with the digital troposcatter modem, are necessary to provide a complete digital troposcatter transmission capability. Modularized RF components such as up/down converters (U/C, D/C) low noise amplifiers (LNA), and power amplifiers (PA) can be assembled into cost effective, reliable packages and provided during the equipment acquisition/system installation phases of a particular transmission upgrade. Other RF components such as circulators, isolators, and dummy loads which are used in the in-place analog system can be retained for use after digitization. Utilization of this approach, where appropriate, will permit the acquisition of new solid state RF components and reliable power amplifiers without purchasing an entire analog troposcatter radio with expensive and complex combiner, demodulator, and service channel functions not required for use with the digital troposcatter modem. Since most DCS troposcatter facilities are geographically concentrated, use of single RF components within a geographical area has the advantage of permitting the establishment of the regionally common logistics base.

Performance assessment and monitoring are of particular importance in troposcatter transmission due to potential ambiguities in identifying and differentiating equipment and propagation related outages. Requirements and methods for the transmission of troposcatter facility component status and performance via the Service Channel Multiplex (SCM) function are under review.

In the interim, Table VIII represents a list of troposcatter facility performance/status functions along with their proposed monitor output formats (contact closure, TTL level, etc) which are likely to be required for telemetering to a transmission control facility. Additional station housekeeping functions such as power amplifier power output and heat exchanger coolant level may be selected for monitoring and telemetering on a site-by-site basis, depending on the particular station manning level.



* Efficient, Reliable High Power Amplifier (ERHPA), or Equivalent

** Commercially Available Components

Figure 9. DCS Digital Tropo Facility (Modular Component Configuration)

TABLE VIII. TROPO FACILITY PERFORMANCE MONITOR/EQUIPMENT STATUS REQUIREMENTS

MONITOR/STATUS FUNCTION	MONITOR/ALARM FORMAT (FUNCTION)
FRAME ERROR RATE THRESHOLD (10^{-3})	FORM C CONTACT CLOSURE (STATUS)
DIVERSITY RECEIVER ACTIVITY	FORM C CONTACT CLOSURES (STATUS)
DIVERSITY TRANSMITTER ACTIVITY	FORM C CONTACT CLOSURES (STATUS)
LOW DIVERSITY TRANSMITTER POWER (3 DB DECREMENT)	FORM C CONTACT CLOSURES (STATUS)
LOSS OF PRIME POWER	FORM C CONTACT CLOSURES (STATUS)
DIVERSITY CHANNEL AUTOMATIC GAIN CONTROL (AGC)	LOW IMPEDANCE ANALOG (MONITOR)
CHANNEL DISPERSION	LOW IMPEDANCE ANALOG (MONITOR)
PREDETECTION SIGNAL TO NOISE RATIO (E.G., EYE PATTERN)	LOW IMPEDANCE ANALOG (MONITOR)
FRAME ERROR PULSES (COINCIDENT WITH FRAME ERROR EVENTS)	TTL LEVEL (MONITOR)

III. DIGITAL TROPOSCATTER TRANSMISSION TECHNOLOGY

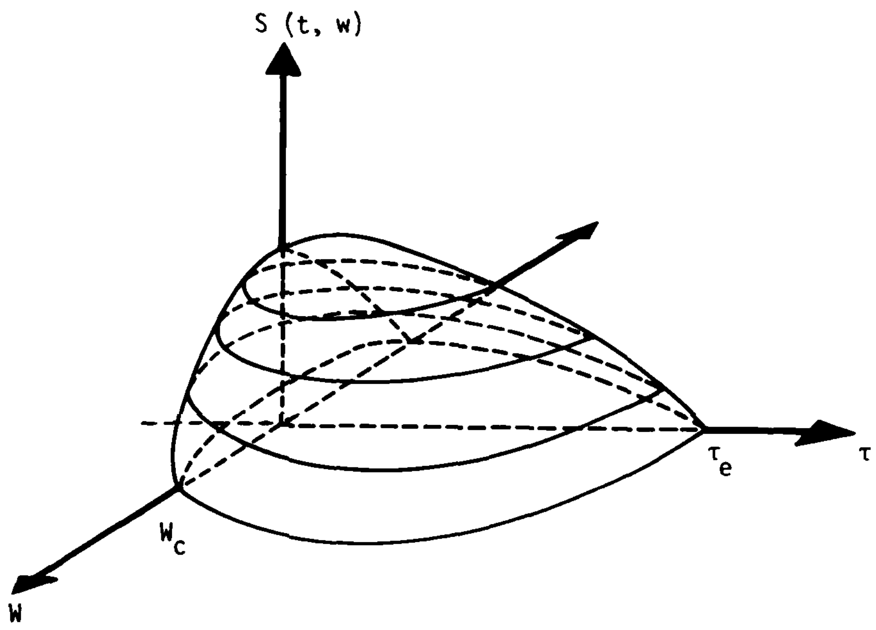
1. THE DIGITAL TROPOSCATTER CHANNEL

Before discussing digital troposcatter transmission techniques, the phenomenon of troposcatter transmission from a digital viewpoint is described. The troposcatter channel is typically described as a linear time varying, double dispersive (in frequency and time), fading channel. Figure 10 is an idealized representation of the scattering function of this type of channel and roughly represents its response to a series of transmitted impulses. For megabit digital transmission (i.e., 3-12 Mb/s), Figure 10 correctly illustrates that the time dispersion or multipath echo (i.e., width along the time axis) of this channel is much larger than the observed amount of frequency dispersion (fading) as related to a transmitted symbol. This large multipath echo phenomenon (frequently extending over one or more times the duration of a transmitted symbol) can cause a degradation in digital transmission performance due to intersymbol interference in which past symbol decisions interfere with the detection of present symbols.

Because intersymbol interference more drastically limits performance at megabit transmission rates, we initially describe the troposcatter channel in terms of its time dispersion or, as mathematically equivalent, in terms of its frequency selectivity. A description of the time dispersion or frequency selective behavior (i.e., doppler shift and fading statistics) of the troposcatter channel is developed at the end of this section in preparation for section IV, which presents DCS digital troposcatter link design objectives.

Due to the bandlimited linear nature of the troposcatter transmission process, its short-term time dispersive fading statistics (i.e., as measured over 10 minutes or less) are generally described in terms of a complex Gaussian, time-varying transfer function [3]. This function is presented as a slice along the time axis of the channel representation, portrayed in Figure 10. In this section, the nature and significance of this transfer function is reviewed in terms of its effect on high rate digital troposcatter transmission.

Since the effect of intersymbol interference on sequential data detection techniques is really a time based phenomenon, the time domain representation of the troposcatter channel has historically provided the most intuitively satisfying description. Therefore, the response of the troposcatter channel is initially modeled in the time domain and related to its alternate frequency domain representation only where necessary. Like any linear filter, the troposcatter channel has an equivalent low pass impulse response, $r(t,\alpha)$, which relates its output, $w(t)$, to an input, $m(t)$, through the convolution integral. That is,



Typical Dimensions

$.1\ Hz < W_c \leq 10\ Hz$

$.1\ \mu sec < \tau_e \leq 1.0\ \mu sec$

Figure 10. Forward Scatter Channel Scattering Function (Idealized)

$$W(t) = \int m(\tau - \alpha)\, r(\tau, \alpha)\, d\alpha \,. \qquad (1)$$

The power impulse response, $r(t,\alpha)$, is unique for a particular troposcatter path and measurement instant, t_m, and its ensemble average over all time, t, is called the delay power spectrum, $Q(\alpha)$. For typical troposcatter links, $Q(\alpha)$ is nonimpulsive and retains significant power for a nontrivial range of time delay (typically on the order of 200-500 nsec).

The nonimpulsive nature of $r(t,\alpha)$ stems from the physical processes inherent in troposcatter propagation. In troposcatter, there are numerous scattering elements within the troposphere which are confined within a common volume subtended by the receive and transmit antenna beamwidths. These elements are highly mobile and power scattering from them causes a time varying temporal dispersion of the received signal (i.e., multipath propagation). In other words, a time specular transmitted signal (e.g., a narrow RF pulse) is transformed into an ensemble of scattered echoes by the channel, each arriving at the receiver dispersed or spread in time. Alternatively described, the variable separation of these scattering elements within the common volume results in time varying constructive and destructive interference patterns at the receiver antenna, causing frequency selective fading. Thus, time dispersion and frequency selective fading are both manifestations of the same basic physical process.

A standard measure of the frequency selectivity of a troposcatter channel is its correlation bandwidth. This parameter identifies the largest transmitted bandwidth which can be expected to fade in a correlated manner (i.e., frequency independent or flat fading) within the channel, or alternatively, the minimum frequency separation required in a frequency diversity configuration to obtain uncorrelated receive signals. A method to derive the correlation bandwidth from the delay power distribution is described in detail later in this section. Here, it is sufficient to note that the frequency correlation function (from which the correlation bandwidth is obtained) is mathematically related to the delay power spectrum since they form a Fourier pair. Thus, if we define δ_s as a quantity equal to the 2σ or double-sided rms value of the delay power spectrum (a convenient measure of its width) and Ω_c as the correlation bandwidth, the following relationship can be derived from a regression analysis of (δ_s, Ω_c) pairs as shown in Figure 11,

$$\Omega_c \leq \frac{2}{\pi \delta_s} \,. \qquad (2)$$

Since the delay power spectrum itself is a time varying process, its variability is briefly explored. A quantitative illustration of the long term behavior of the delay power spectrum is seen in Figure 12, which presents a distribution of δ_s, as calculated from measured data on a number of medium distance troposcatter links. Because of

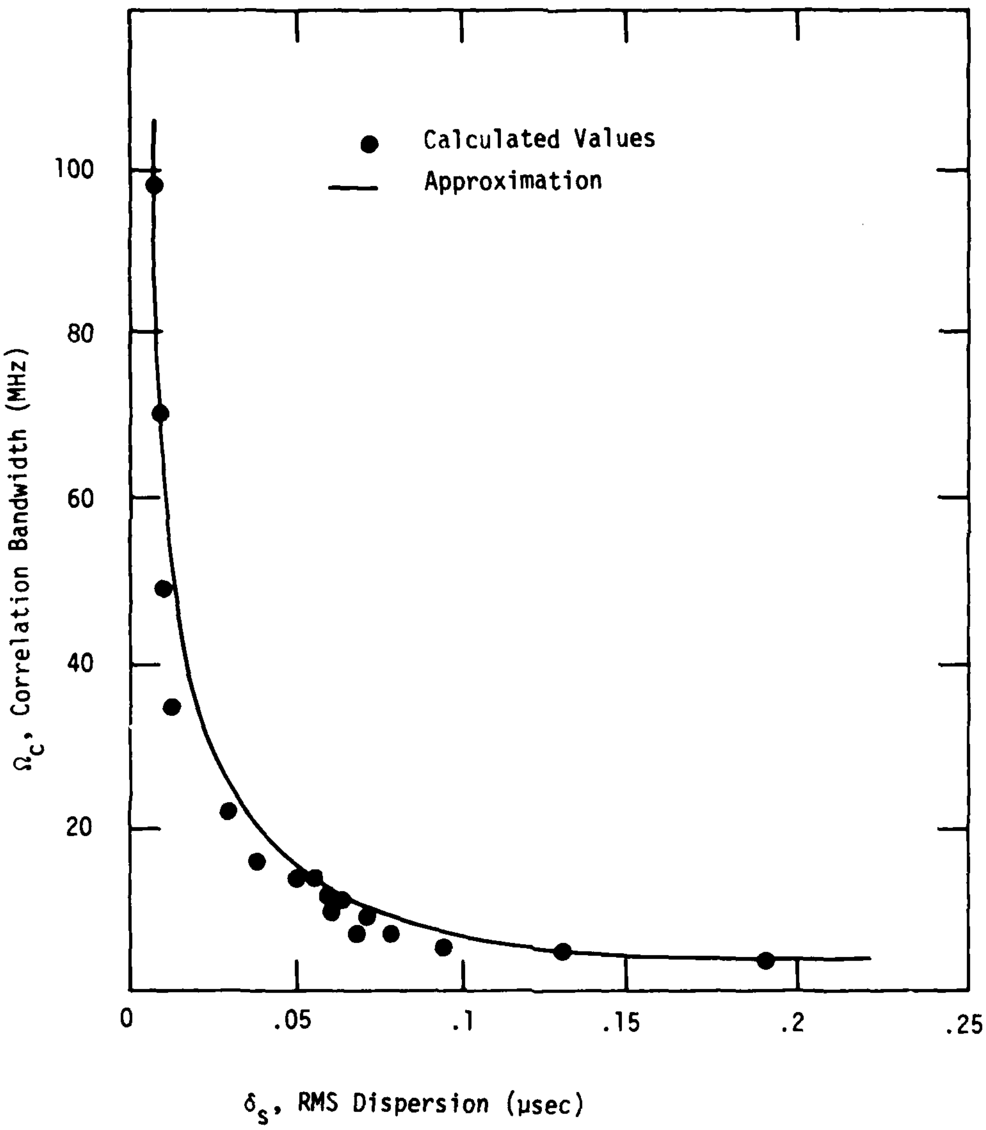


Figure 11. Relationship of RMS Channel Dispersion to Correlation Bandwidth

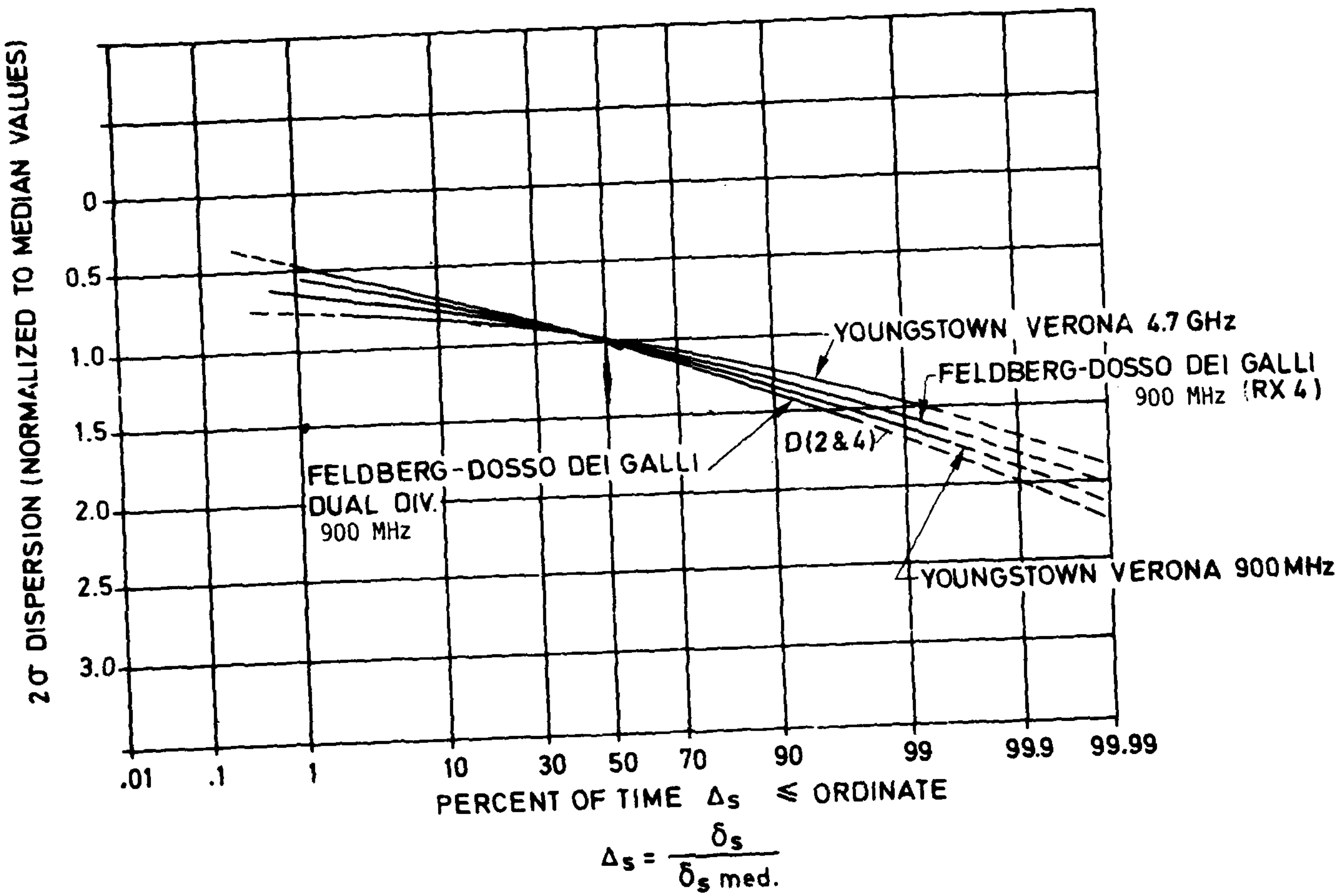


Figure 12. Cumulative Distribution of Normalized Multipath Dispersion

the Fourier relationship between the delay power spectrum and the frequency correlation function, the behavior of Ω_c is expected to be equivalently stochastic.

As implied by the long term cumulative distributions shown in Figure 12, $Q(\alpha)$ is expected to be functions of both link parameters and path conditions. The expected variation of $Q(\alpha)$ with path conditions (specifically changes in effective earth radius) is shown in Figure 13. It is instructive to consider Figure 12 and Figure 13 in light of Figure 14 (taken from Panter [4]), which tabulate the measured K factor distribution over a one year period and point to the expectation of rather large values of δ_s as measured over an operating year. As seen in Figure 12, measured data indicate worst hour values of δ_s up to 2.5 times the yearly median value. Consideration of these figures implies the need for efficient accommodation of large amounts of multipath propagation (on the order of 400-500 nsec for medium length L or S Band paths) if reliable digital transmission is to be achieved at required DCS capacities.

The channel is now described from a frequency dispersive or time selective viewpoint (i.e., its "fading" behavior) because in section IV, system performance concepts for digital troposcatter links are based heavily on the temporal statistics of troposcatter fades. Thus, a brief description of the fading behavior of the troposcatter channel is useful in clarifying the digital troposcatter link performance analysis presented herein.

The fading behavior of the troposcatter channel is typically portrayed as resulting from a compound fading process. The short-term fading characteristic (measurable over portions of an hour) is accurately described by Rayleigh statistics. As for its longer term behavior, the troposcatter channel experiences large diurnal variations (typically 20-30 dB) compounded by a seasonal variation on the order of 6-10 dB. Figure 15 portrays these fading modes and their typical dynamic ranges. Because of this rather complex fading behavior, troposcatter fading is conventionally described in the overall sense as having a log - normal distribution of short term median signal levels with shorter term (fractions of a second) fading about each median value being described by Rayleigh statistics. Accepted methods of calculating the magnitude and distribution of the long term path loss can be found in NBS Technical Note 101 [5] and the recommendations of the CCIR [6] for transmission frequencies below 2 GHz. For frequencies above 2 GHz a new procedure has been developed under the US Army's Angle Diversity Program [7].

Equally important to the discussion of troposcatter fading and its relation to communications system performance is a description of expected fade rates. In particular, short term fading as described by the mean short term fade rate, N, will be most apparent (since long term fading is much slower) and for the troposcatter channel, strongly frequency dependent. The

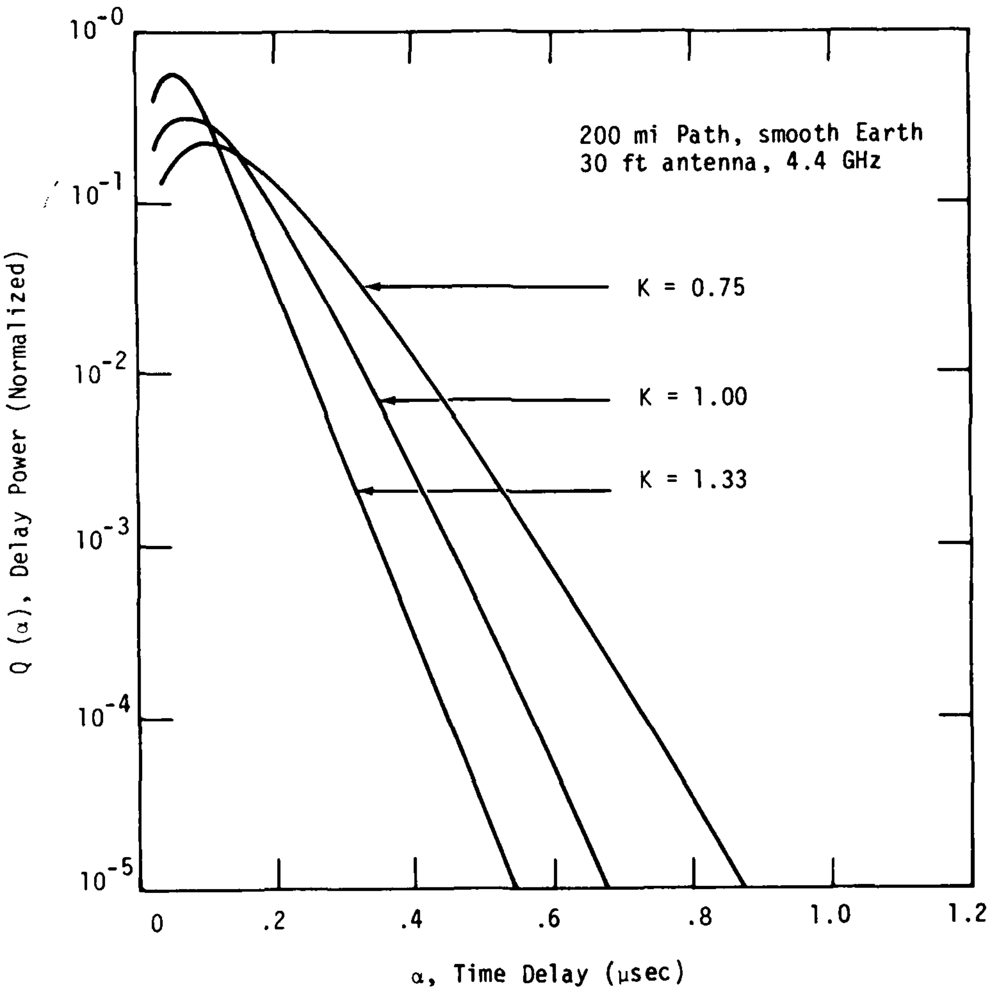


Figure 13. Delay Power as a Function of Effective Earth Radius

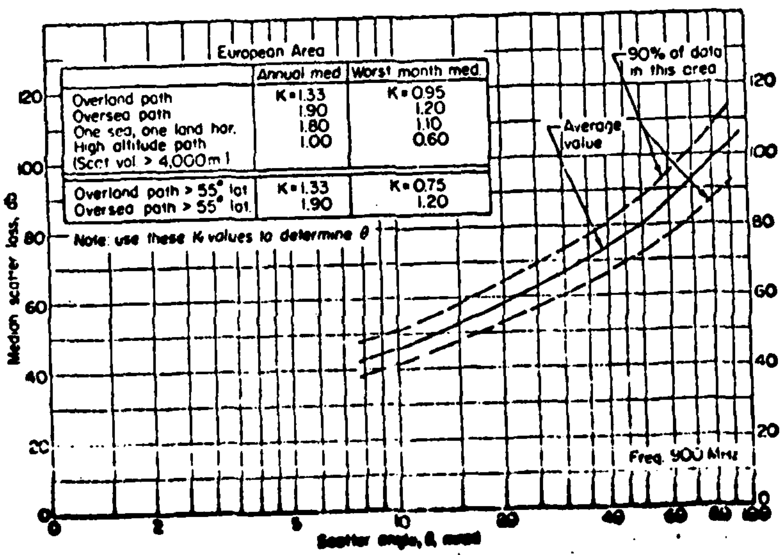


Figure 14. European K Values

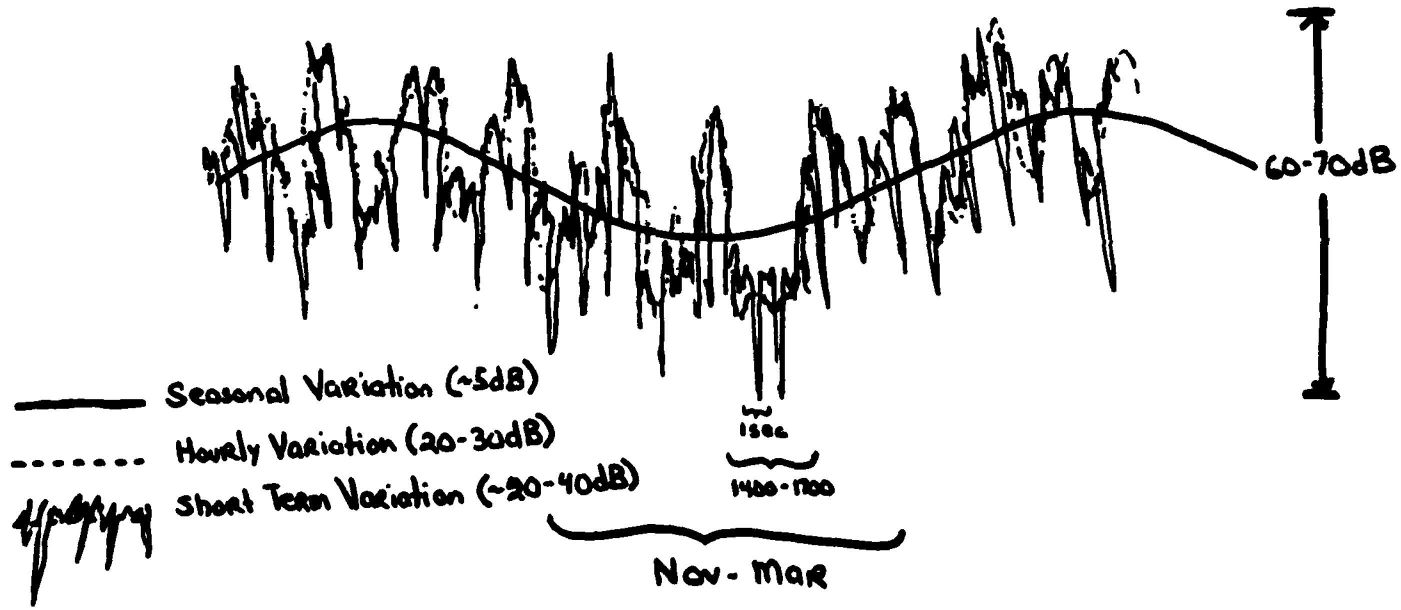


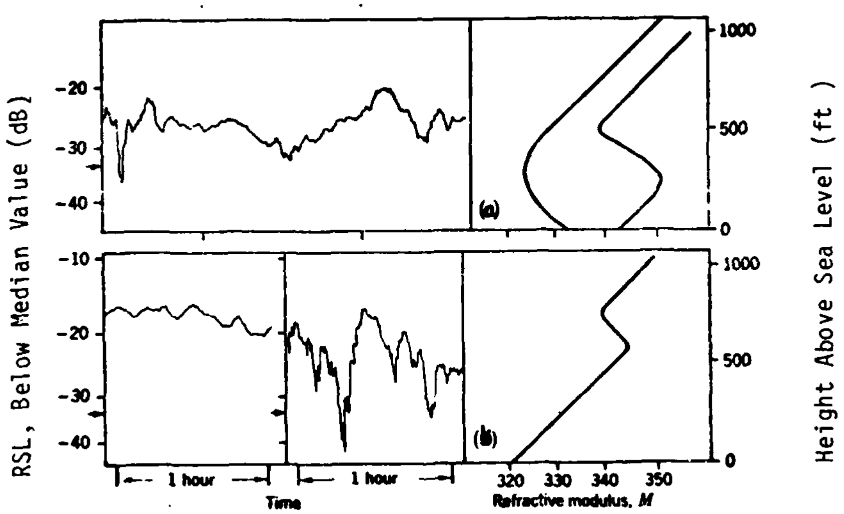
Figure 15. Troposcatter Fading Behavior (Typical Non-Diversity)

dependence of short term fade rate on carrier frequency is explored in [8]. For DCS troposcatter links (which operate primarily in three bands between 700 MHz and 5.0 GHz) a mean fade rate of 0.1 Hz represents a reasonable estimate and is used in the subsequent development of digital troposcatter link design criteria.

Because of the variability of troposcatter propagation during unusual atmospheric conditions, periods of extraordinary propagation can occur. The performance of troposcatter transmission systems during these anomalous periods can be enhanced or degraded depending on the limitations of a particular system design. There are two anomalous propagation modes that are of major significance to DCS troposcatter transmission engineering. The first anomalous condition is evidenced during periods when the refractive index profile of atmosphere is altered. As illustrated in Figure 16(a), this condition results in the creation of a relatively low loss transhorizon propagation mode. This mode is generally identified by enhanced received signal levels (typically increased by 10-20 dB) and a reduced fade rate (typically decreased by a factor of ten). This period of large scale stationarity, called surface ducting, is also identified by a decrease in multipath dispersion since ducting physically stems from refractions from a propagation channel that is strongly stratified and reduced somewhat in vertical dimension. The designer of digital troposcatter transmission systems must consider the occurrence of surface ducting so that saturation of the RF circuitry does not occur. For links transversing or parallel to coastlines in several geographic areas, the Mediterranean and S.E. Asia, surface ducting conditions are common.

Another form of ducting, elevated ducting, is illustrated in Figure 16(b). Elevated ducting can actually result in a period of decreased performance. This is due to a trapping of the transmitted field away from the maximum gain orientation of the receive antenna (i.e., away from the nominal great circle path). The probability of occurrence of elevated ducting in DCS troposcatter links can be ascertained by reviewing long term performance data on a link basis, if available. If such data are unavailable, fortuitous periods of path loss testing is the only way that this phenomenon can be reliably detected. Local meteorological data should also be reviewed, if available, for severe index of refraction variations. The use of meteorological data is expected to become more commonplace in both path loss prediction and furthering the understanding of the basic scattering process.

The other major anomolous transhorizon propagation mode occurs when an aircraft passes through the scatter volume outlined by the intersection of transmit and receive antenna patterns, presenting itself as the dominant scattering element.



(a) Surface Duct

(b) Elevated Duct

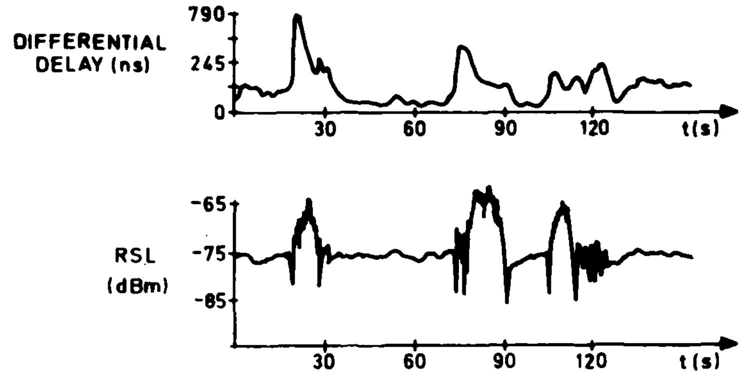
Figure 16. Atmospheric Ducting

There are two separate effects which are felt during this anomaly. The first and most obvious effect is that a temporary increase in path fade rate (up to 100 Hz) is experienced due to the doppler shift caused by specular reflection from the moving aircraft as it traverses the common volume. The second major effect is the temporary enhancement of the received signal levels due to specular reflection from the surface of the aircraft. This effect must be considered in the design of the digital troposcatter modem to minimize the probability of system synchronization loss due to the discontinuity in propagation delay between aircraft scatter and the normal troposcatter propagation mode as the aircraft enters and leaves the common volume. Figure 17 illustrates the RSL and multipath dispersion characteristics typical of aircraft passages.

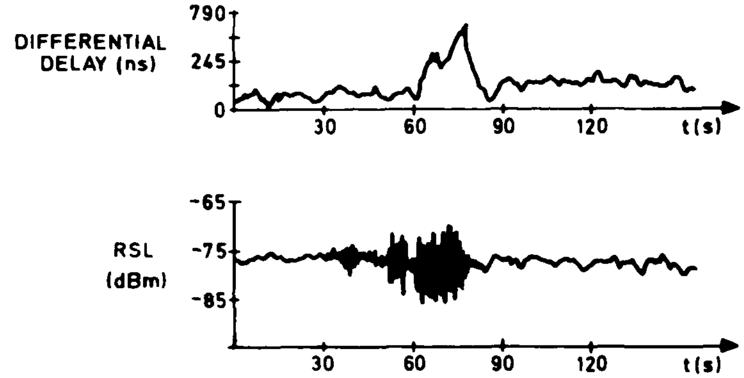
2. IMPLICIT DIVERSITY

Frequency selective fading has historically limited the performance of multichannel analog (FDM/FM) troposcatter systems. For FDM/FM systems, frequency selective fading of the transmitted spectrum due to multipath propagation causes an increase in system noise called "path intermodulation" and limits the achievable channel capacity on most troposcatter links. Similarly, megabit rate data normally occupy transmitted spectra several times the value of the channel correlation bandwidth and thus are also vulnerable to digital path intermodulation or "intersymbol interference" resulting from independent fading of various regions of the transmitted spectrum. However, with the use of adaptive signal processing, advantage can be taken of frequency selective fading across the transmitted spectrum to provide a significant increase in available system gain. This increase in system gain is brought about by the coherent recombination of uncorrelated, selectively fading segments of the the transmitted spectrum. This in-band diversity phenomenon is denoted as "implicit" diversity to distinguish it from the diversity gained through "explicit" means (i.e., additional receiver frequencies, antennas, or feedhorns in the case of angle diversity). The relationship of multipath propagation to implicit diversity is briefly explored after which the performance advantage obtainable through the use of implicit diversity can be estimated. This area is addressed below as background prior to a review of digital troposcatter technology and the subsequent derivation of link design criteria for digital troposcatter.

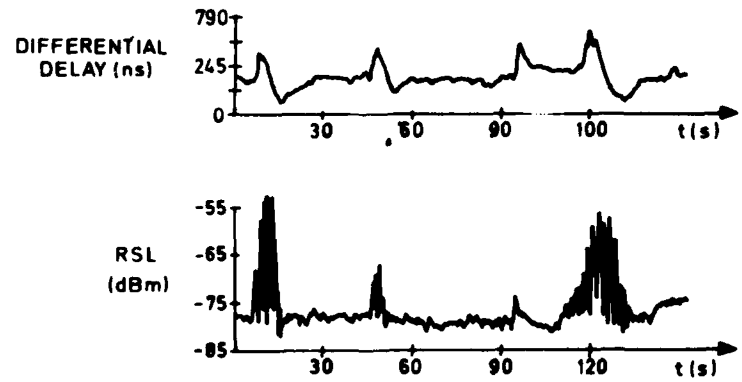
In order to more accurately treat the concept of implicit diversity, a mathematical review of the details of frequency selective fading is useful. While many channel models have been proposed to represent the frequency selectivity or time dispersion of the troposcatter channel [3, 8, 9, 25], only the Bello and Parl models with their concept of the delay power spectrum



a: AIRCRAFT PASS - MODE I



b: AIRCRAFT PASS - MODE II



c: AIRCRAFT PASS - MODE III

Figure 17. Examples of RSL and Dispersion Measured During Aircraft Passes

are based on physically fundamental concepts, and thus more accurately describe frequency selective behavior. In fact, these models have been shown to be especially accurate for paths in excess of 150 miles (242 km) and therefore of direct utility to the DCS. Both the Bello and Parl multipath dispersion models depend, in turn, on the Wide Sense Stationary Uncorrelated Scatter (WSSUS) representation for their theoretical basis.

According to the WSSUS model, we see that the delay power spectrum can be defined as

$$Q(\alpha) = \langle r^*(\alpha)\, r(\alpha) \rangle \tag{3}$$

where $r(\alpha)$ was defined previously and $\langle \cdot \rangle$ represents its ensemble average. Recognizing that the WSSUS channel allows a Fourier relationship between the delay power spectrum and the complex Two Tone Frequency Correlation Function, $R(\omega)$, it is possible to express $R(\omega)$ similarly:

$$R(\omega) = \langle G(\omega)\, G^*(\omega + \omega_r) \rangle \tag{4}$$

where $G(\omega)$ represents the Fourier transform of $R(\omega)$ and ω_r is the frequency spacing (in radians).

Figure 18 illustrates the shape of $R(\omega)$ calculated for a medium range UHF troposcatter link that is similar to many DCS links and that serves as an example for more fully discussing the concept of correlation bandwidth. Of specific interest is the frequency correlation coefficient, $\rho(\omega)$, defined as

$$\rho(\omega) = \frac{R(\omega)}{R(0)} . \tag{5}$$

The magnitude of ρ is a quantitative indication of the statistical dependence which exists between two transmitted signals. Previous work [10] has indicated that two fading signals can be treated as statistically independent if ρ is on the order of $1/e \approx (0.4)$. Thus if $R(\omega)$ is continuous, the value of ω by which one can obtain $\rho = 0.4$ is definitive of the correlation bandwidth of the fading process (i.e., fading within the correlation bandwidth is essentially nonselective). For the troposcatter link modeled in Figure 18, $\rho(.4)$ is on the order of 5 MHz. This indicates that the transmission of an RF spectrum occupying 5 MHz or greater is affected by frequency selective fading. Frequency selective fading catastrophically affects the performance of conventional digital transmission systems due to the inability to maintain carrier coherence and symbol timing. However, as will be described later, the application of special processing techniques can actually utilize this decorrelated fading and develop an "in-band" or implicit diversity gain.

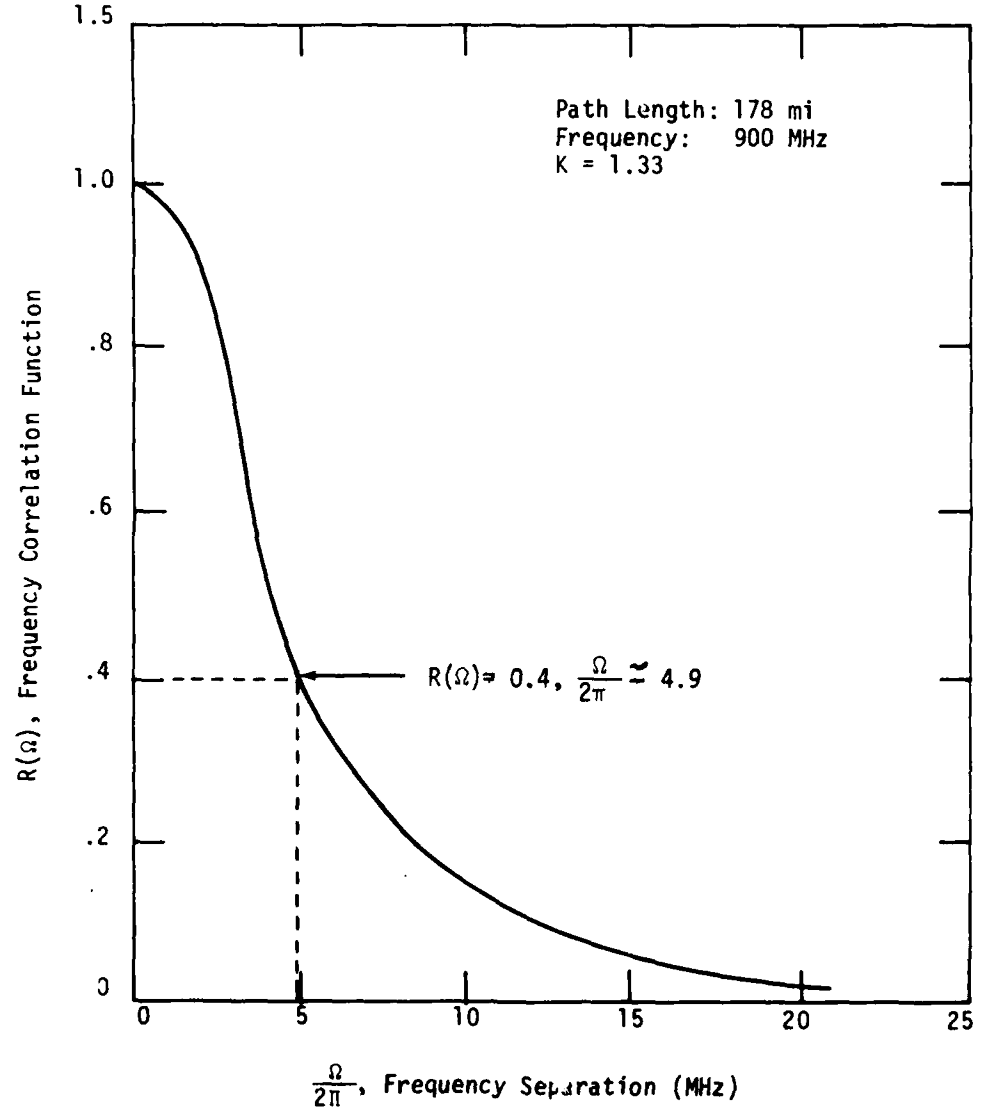


Figure 18. Frequency Correlation Function for a Typical Medium Distance Path

The mathematical relationship of the correlation bandwidth to the delay power spectrum and its relationship to the concept of implicit diversity can now be developed. Continuing with WSSUS channel notation, it is possible to express the shape of the delay power spectrum as an exponential after Sherwood [11],

$$Q(\alpha) = s^2 \, EXP[-s\alpha] \tag{6}$$

with Fourier transform

$$G(\omega) = \frac{s^2}{(s + j\omega)^2}, \tag{7}$$

where s is a link sensitive parameter which can be determined from a curve fit of $Q(\alpha)$ to a specific delay power spectrum. An expression for $G(\omega)$, which is fairly representative of medium length and longer troposcatter paths, can be expressed indirectly through the envelope correlation coefficient:

$$\rho = \left[\frac{1}{1 + \left(\frac{\omega}{s}\right)^2}\right]. \tag{8}$$

Thus, from a computed value of s it is possible to calculate a corresponding bandwidth, ω_c , which is suitable for estimating the implicit diversity potential of a particular link. Upon calculation of ω_c , the order of implicit diversity can then be estimated by forming the ratio of the transmitted to correlation bandwidths.

That is,

$$\eta_i \cong \left| \frac{B}{\omega_c} \right\rangle \tag{9}$$

where η_i = Approximate number of implicit (i.e., inband diversity) paths available for diversity reception
B = The transmitted bandwidth, as defined by its 10 dB points (MHz)
ω_c = Correlation bandwidth (MHz)
$|\cdot\rangle$ = Largest integer operator (i.e., n + ε = n + 1 for $0 \leq \varepsilon < 1$).

The basis for estimating η_i in the above manner is appropriate. It has been shown that statistically independent signals with large amplitude differentials (up to 10 dB) can effectively provide a diversity improvement. Thus, even if only a fraction of the scattered power falls outside of an integral number of correlation bandwidths, it still contributes in a diversity manner.

Since the calculation of n_i has as its basis the concept of a delay power spectrum which is defined as an ensemble average, n_i really represents the expected number of implicit diversity paths present in the channel. The subsequent application of n_i to the estimation of average digital performance follows. For a particular mean signal to noise ratio, γ_o , the mean DPSK bit error probability for a channel with a known n_i can be estimated as

$$\langle P_e \rangle = \frac{1}{2}\left[1+\hat{\gamma}_o\right]^{-n} \tag{10}$$

where $\hat{\gamma}_o = \frac{\gamma_o}{n_i}$ (Mean signal to noise ratio modified to account for inband power sharing)

and $n = n_i \cdot n_e$ (Total number of diversity paths which is the product of the number of explicit and significant implicit paths).

Figure 19 illustrates the expected improvement in average error probability, $\langle P_e \rangle$, as a function of n_i and n_e . From this figure, it is obvious that implicit diversity has potential cost savings when compared to explicit diversity techniques, which require additional hardware or frequency allocations.

3. DIGITAL TROPOSCATTER TRANSMISSION TECHNOLOGY

Prior to the development of modulation techniques specifically for DCS application, digital troposcatter transmission was limited to less than 3 Mb/s. Digital modulation techniques such as Binary Frequency Shift Keying (BFSK) and Phase Shift Keying (PSK) were typically used. Because of the relative simplicity of the nonadaptive receiver structures implemented with these techniques, their performance was sharply curtailed by even a modest amount of multipath propagation [12]. Later, compound modulation schemes (e.g., FSK/PSK) were used to separate adjacent symbols in a bandwidth inefficient attempt to further mitigate the effects of multipaths [13]. Bandspread systems using correlation receivers (e.g., the RAKE) were also implemented to take advantage of the diversity inherent in the frequency selective, multipath channel. However, the bandspreading approach was grossly inefficient in its use of transmitted bandwidth.

The advent of adaptive signal processing techniques [14, 15] together with the utilization of more efficient modulation forms such as QPSK and Minimum Shift Keying (MSK), have enabled bandwidth efficient transmission at digital rates up to four times the previous limit. The successful implementation of these techniques, with their near optimum utilization of implicit diversity has, essentially removed the data rate limitations resulting from intersymbol interference.

a. Comparison of the DAR and MD-918/GRC Modems. Over the past 8 years the Army and Air Force have performed RDT&E on several techniques for DCS Digital Troposcatter implementation. After their development and optimization, these techniques were evaluated in a

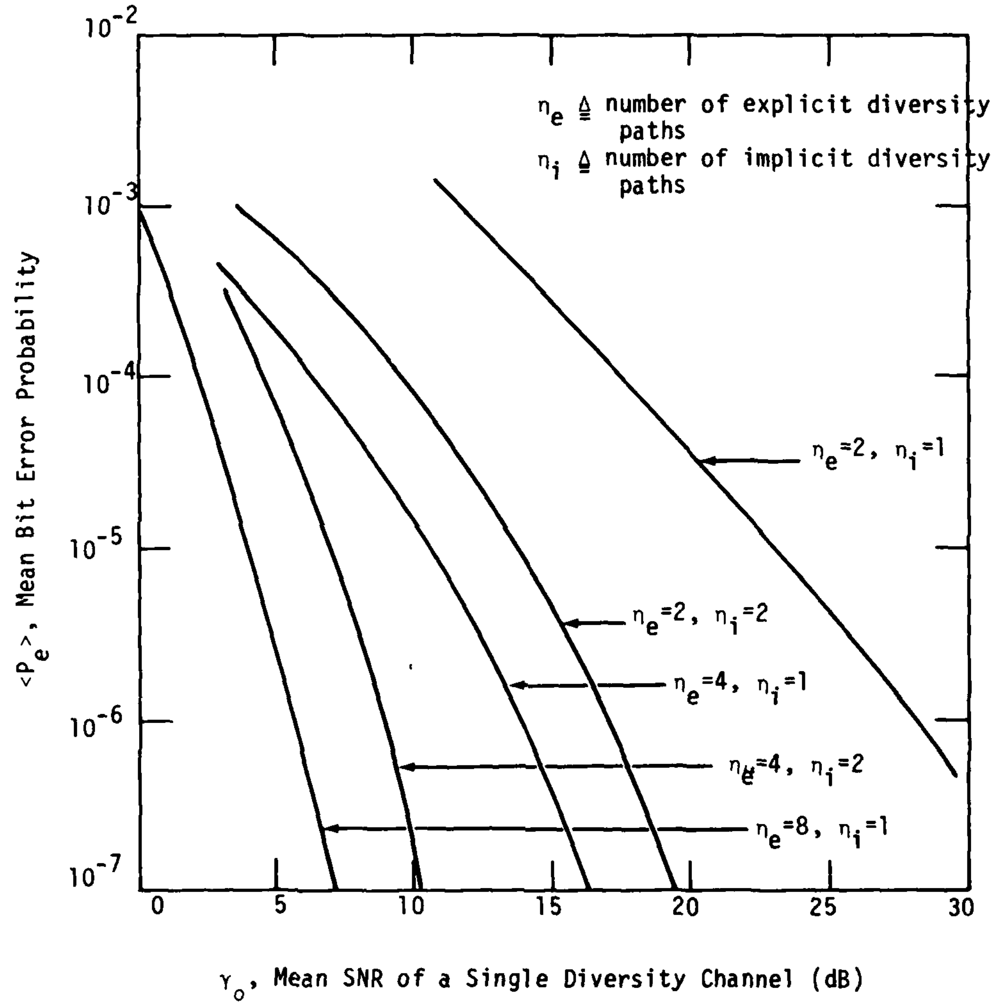


Figure 19. Mean Bit Error Probability and Implicit Diversity for DPSK

series of performance tests to determine their relative applicability to the DCS and to provide a data base for technical specification purposes. The following discussion briefly explains the underlying concepts of these techniques and the results of the comparative evaluation. For a more rigorous treatment of the technologies, the reader is encouraged to obtain the references cited in the following discussion.

The first technique that is discussed is Adaptive Decision Feedback Equalization (ADFE). This technique, described in some detail in the literature [14], embodies a transversal equalizer structure in which channel adaptation is accomplished via decision directed feedback. In general, equalization techniques can be categorized into linear and feedback classes. For diversity troposcatter transmission, implementation of a linear equalizer, as illustrated in Figure 20, would utilize an ensemble of linear filters, each operating on a particular diversity branch. The equalized diversity signals could then be additively combined prior to sampled data detection. Linear modulation such as PAM, FSK, PSK, or MSK must be used due to the linear nature of the receiver structure. Equalizer adaptation is typically accomplished via a training sequence or pilot tone, depending on the implementation of the equalizer. However, decision directed adaptation can also be used.

A feedback equalizer, Figure 21, is similar in structure to the linear equalizer with the exception that it provides data feedback through a return path where a filtered version of the reconstructed data sequence can be added into the data decision process. This permits partial cancellation of intersymbol interference from previously detected data bits. As with the linear equalizer, its optimum implementation consists of a series combination of matched and transversal filters for each diversity path. The transversal filter, if properly adapted, will reduce channel caused intersymbol interference, while the matched filter will provide an implicit diversity advantage through coherent recombination of the delayed components of the multipath signal structure. Due to the bandlimiting imposed by practical system constraints, the received signal is also bandlimited, and therefore a single realizable transversal filter, suitably adapted, can provide the required series filter characteristics.

As mentioned before, this receiver structure can be adapted via a training sequence or through decision directed means. The current ADFE digital troposcatter modem prototype (MD-918/GRC) which was developed under the U.S. Army Megabit Digital Troposcatter Subsystem (MDTS) program, is implemented with decision directed adaptation. Adaptation via the transmission and processing of training bits provided by the modem is also possible. In fact, since the DCS digital troposcatter modem will have an internal time division multiplexer (TDM), the application of Adaptive Reference Directed Equalization (ARDE) can be considered for this modem if the aggregate

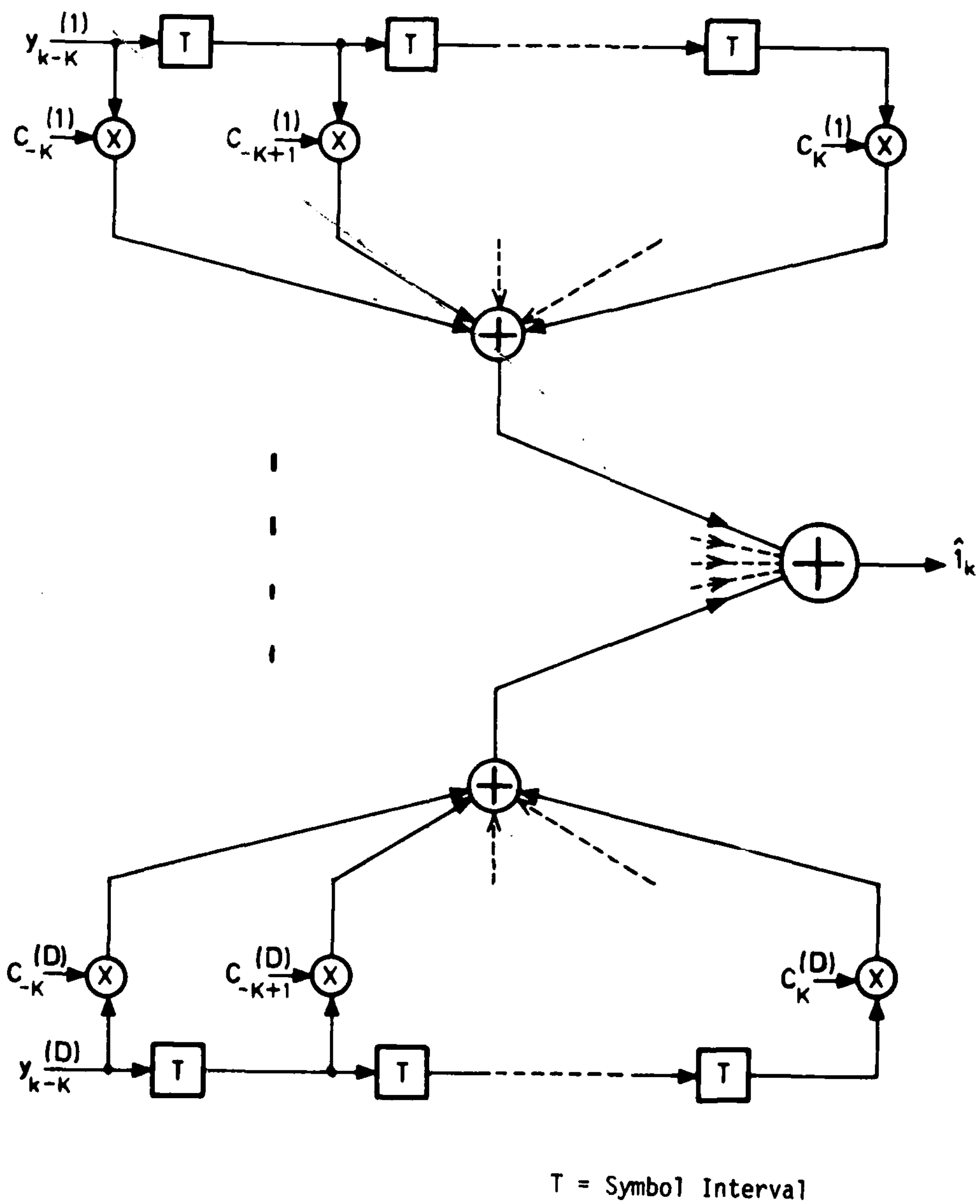
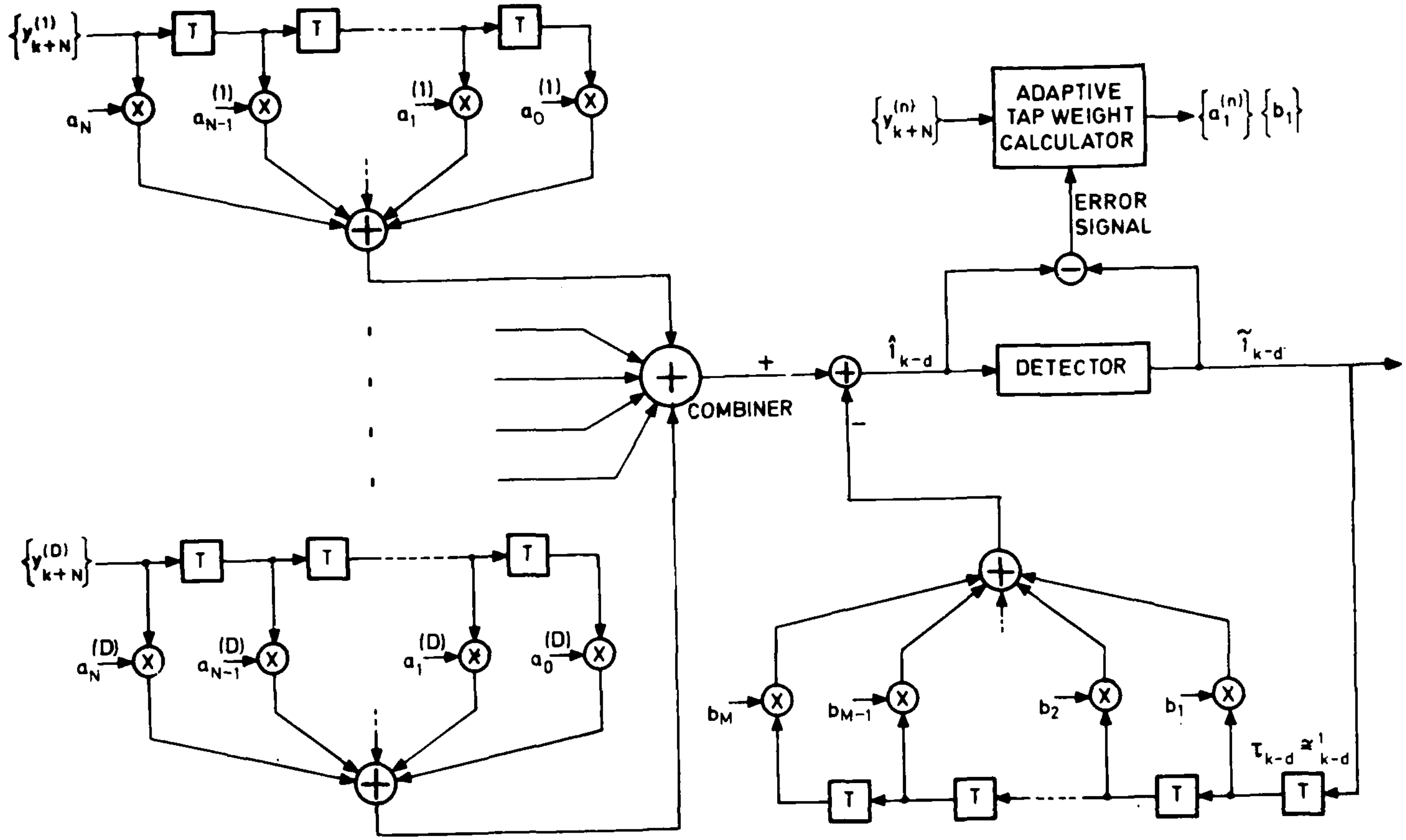


Figure 20. Linear Transversal Equalizer



T = Symbol Interval

Figure 21. Decision Feedback Equalizer With Diversity Reception

TDM rate (sum of data inputs plus framing reference required for adaptation) can be within the bandwidth constraints specified in section II. The primary advantage of reference directed feedback is that it is generally more robust under degraded transmission conditions and thus is more desirable for low diversity (e.g., non and dual) applications where deep fades occur more frequently or under interference (e.g., jamming) conditions. However, for higher order diversity implementations, ADFE is seen to be intrinsically superior to reference directed feedback in that ADFE avoids any transmission penalty attributable to an increased noise bandwidth resulting from the transmission of an additional adaptation bit sequence. Estimates of the required training sequence rate are dependent on the range of fade rates which must be accommodated. As an example, satisfactory operation on links with fade rates of 1-10 Hz is likely to require the transmission of a 150-200 kb/s adaptation frame rate.

Because the ADFE is described as a channel adaptive structure, the currently implemented adaptation technique is briefly described. As mentioned previously, both the linear equalizer and the feedback equalizer can be adapted, via decision directed methods, to provide acceptable performance in a channel whose impulse response is randomly changing. The specific criterion used for adaptation in the MD-918 is based on minimization of the Mean Square Symbol Error (MMSE). As shown in Figure 21, the MMSE signal is formed in the modem from a voltage obtained from the difference between the integrate and dump circuit output (prior to slicing) and a reference amplitude. This error signal is then filtered to minimize the effects of noise and then is correlated with appropriately delayed samples of the input signal. These correlations are then used to develop weights by which to weigh the received multipath components. While a truly optimum criterion would be based on minimum bit error probability, MMSE permits a greatly simplified implementation through the use of gradient estimation adaptation algorithms and performs almost equivalently for most channels of interest.

The primary function of the feedback path is to reduce intersymbol interference and thus permit a less costly modem implementation. For a given level of performance (defined in terms of minimizing intersymbol interference), fewer forward equalizer taps are required when a feedback path is supplied.

The design criteria of the ADFE approach to digital troposcatter transmission are basically twofold. The first, and most important, is the ability of the ADFE to reduce the effects to multipath propagation (i.e., intersymbol interference). This capability is determined by the number of forward and backward equalizer taps. For example, the use of a three tap forward equalizer with intertap spacing of one-half of the transmitted symbol duration together with a three tap backward equalizer will permit the near optimum equalization (i.e., result in acceptable residual intersymbol interference) of diversity troposcatter paths with a δ_s or double sided rms dispersion (2σ) of up to $1.5T_s$, where T_s is the transmitted symbol duration. For channels with greater than $1.5T_s$, error correction voltages obtained in the backward equalizer begin to be significant and tend to prevent the buildup of a large amount of residual intersymbol interference. However, the performance of the ADFE in the region of $2\sigma > 1.5T_s$ is not discontinuous and is seen to be strongly dependent on the explicit diversity configuration. In fact, the present ADFE in a quad diversity implementation will accommodate paths with a 2σ of up to $2T_s$ with little ($\approx$ 1 dB) degradation from its optimum operating point. A typical 300 mile (480 km) DCS troposcatter link has a yearly median multipath (2σ) on the order of 200-300 nsec.

Eventually, as the rms channel dispersion increases beyond the capability of the backward equalizer to correct for the estimated intersymbol interference, the performance of the ADFE structure will begin to degrade and exhibit an irreducible error rate. In order to extend the range of the equalizer to accommodate larger multipath spreads caused by, for example, seasonal path variations on long paths, the addition of more forward equalizer taps or additional diversity is usually indicated (although an increase of backward equalizer taps to develop correction voltages based on a greater number of previously detected symbols may suffice and will be less costly).

The second design sensitivity of the ADFE technique lies in its ability to utilize multipath propagation as implicit diversity. This capability is related to the intertap spacing of the forward equalizer. This can be easily visualized by considering the operation of the forward equalizer in the time domain. In the time domain, the equalizer is seen as being able to coherently combine "m" of a possible "n" scatter paths, where m is essentially the number of forward equalizer taps. For a particular rms channel dispersion, extension of overall delay capability beyond the expected range of RMS dispersion will not in general provide any significant additional implicit diversity gain. This is due to the extremely low power contained in scattered components received outside the 2σ dispersion ($\mathcal{E}_s$) of the particular channel. However, a significant number of partially correlated paths arriving within an interval bounded by the 2σ dispersion are present (the exact number of paths is functionally dependent on the composition and dynamics of the scatter volume). These paths can be optimally combined only if the intertap spacing is on the order of the granularity of the multipath structure of the channel. Although many of these scatter-components are partially correlated, they nevertheless can contribute effectively in a diversity manner (equation [10]). The span of the equalizer (i.e., total delay or aggregate sum of the individual tap delays) will, of course, remain constrained by the maximum 2σ channel dispersion which must be accommodated. The present ADFE structure as implemented in the MD-918/GRC Modem (three forward equalizer taps) can recognize no more than three inband paths. This implies a similar upper limit in achievable implicit diversity (i.e., third order). A reduction of the intertap spacing to $T_S/3$ or less would permit a greater potential to utilize implicit diversity as long as the same total forward equalizer span is provided.

The implementation of the ADFE as a prototype modem by the U.S. Army in the Megabit Digital Troposcatter Subsystem (MDTS) (MD-918/GRC) program has demonstrated significant performance gains based on a number of simulated link multipath profiles and actual link tests at rates up to 12.6 Mb/s. These results are typified by Figures 22 through 24.

The second technique which was actively considered for DCS application is transmitter time gating with coherent detection. This approach is currently implemented in the Distortion Adaptive Receiver (DAR) Modem developed by the USAF [15]. The DAR technique employs transmitter time gated QPSK modulation, Figure 25. The dispersive troposcatter channel acts as a transmitter filter and will "fill-in" the guard space (τ) or time gate, thus avoiding significant intersymbol interference as long as the guard space is less than the significant instant (i.e., 2σ value) of the channel inpulse response. Since the channel fade rate (or, change rate) is always very much less than the transmitted symbol rate, the receiver will see a serial stream of many symbol pulses, each identically distorted, with the exception that they will differ in phase in accordance with the modulator phase state. If, through decision feedback, a coherent reference pulse train can be derived (mirroring the path induced amplitude and phase characteristics of the received signal), matched filter detection can be implemented with the important benefit of near optimum utilization of implicit diversity.

Because implicit diversity is key to the DAR technique and because development of a coherent reference is the key to the realization of implicit diversity, the details of the DAR reference generation technique are described. Basically, a reference pulse train is generated in the receiver at the IF frequency via an "inverse modulation" process where previous bit decisions are used to phase shift suitably delayed transmitted symbols such that all symbol phase states are equal (modulo 2π). This "coherent reference" is then applied to a recirculating filter where the reference signal-to-noise ratio is improved by coherently adding reference pulses while the noise in the filter loop adds incoherently (i.e., as the rms of the noise voltage). Additionally, the effect of decision feedback errors is reduced since no one reference pulse is uniquely used to detect a transmitted symbol.

However, the utilization of transmitter time gating to provide multipath immunity is not without constraint. Lengthening the time gate to increase the guard time against multipath sacrifices transmitted power and eventually results in an unrecoverable power loss and a spreading of the transmitted spectrum in excess of the allocated bandwidth. These factors strongly imply an upper bound on achievable data rate or acceptable multipath delay. A partial

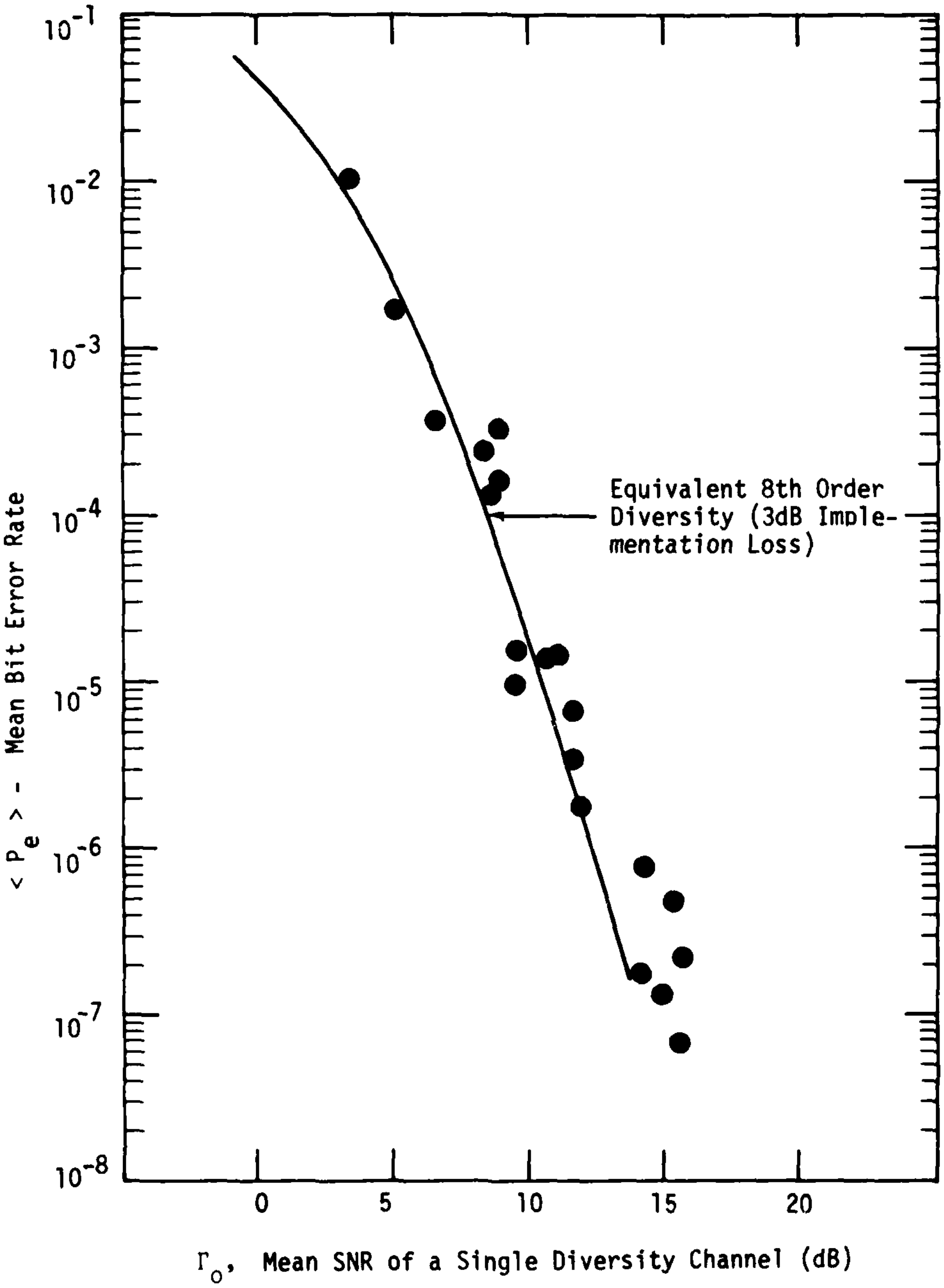


Figure 22. MDTS Over-the-Air Performance
Youngstown - Verona (168 Mi)
6dBNF, AN/TRC-132A
6.3 Mb/s, Quad Diversity

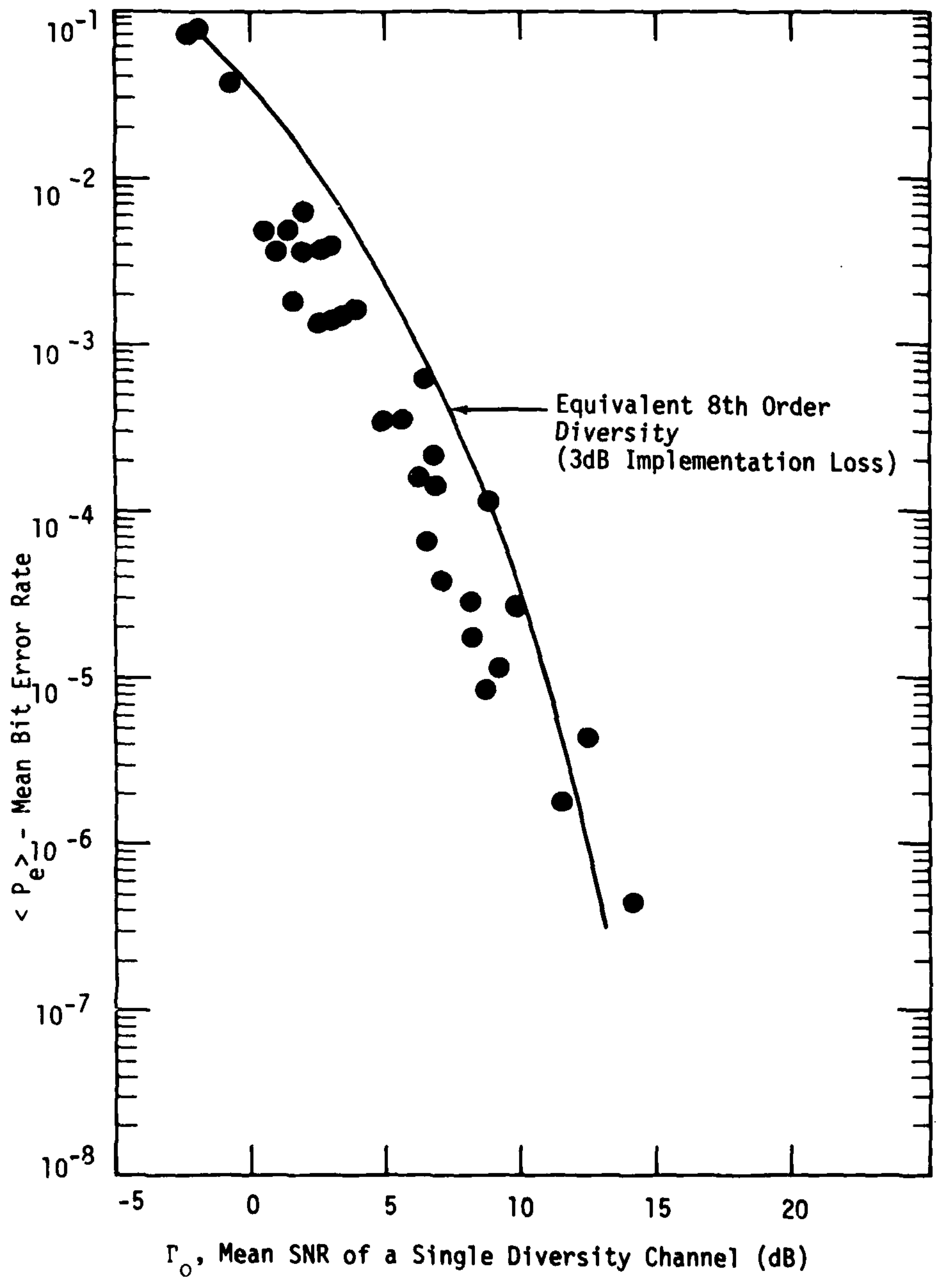


Figure 23. MDTS Over-the-Air Performance
Youngstown - Verona (168 Miles)
C - Band, Quad Diversity
6dBNF, AN/TRC-132A
12.6 Mb/s

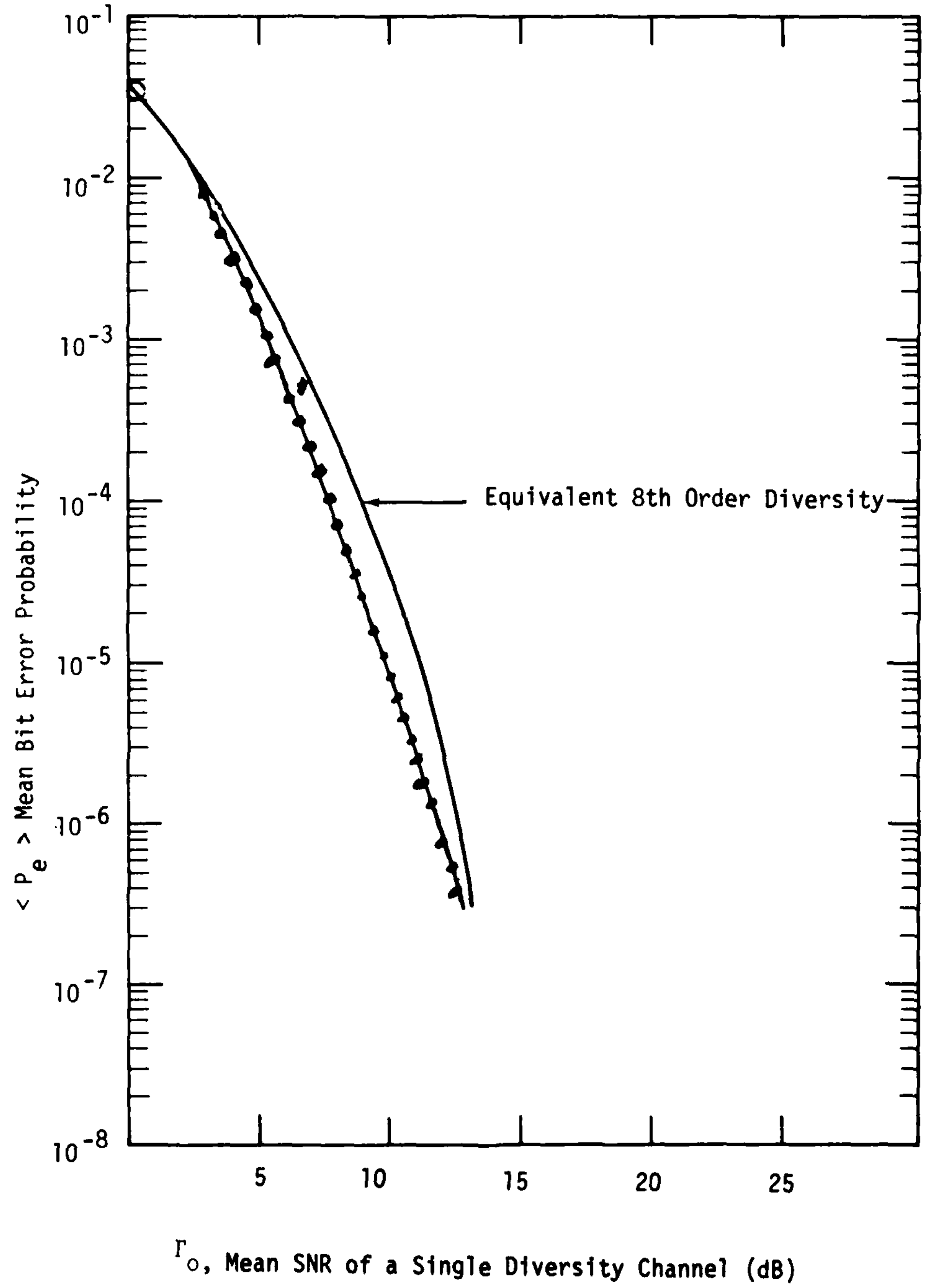


Figure 24. MDTS Media Simulator Performance
250 Miles, .6° Antenna BW, k = 4/3, 6.3 Mb/s

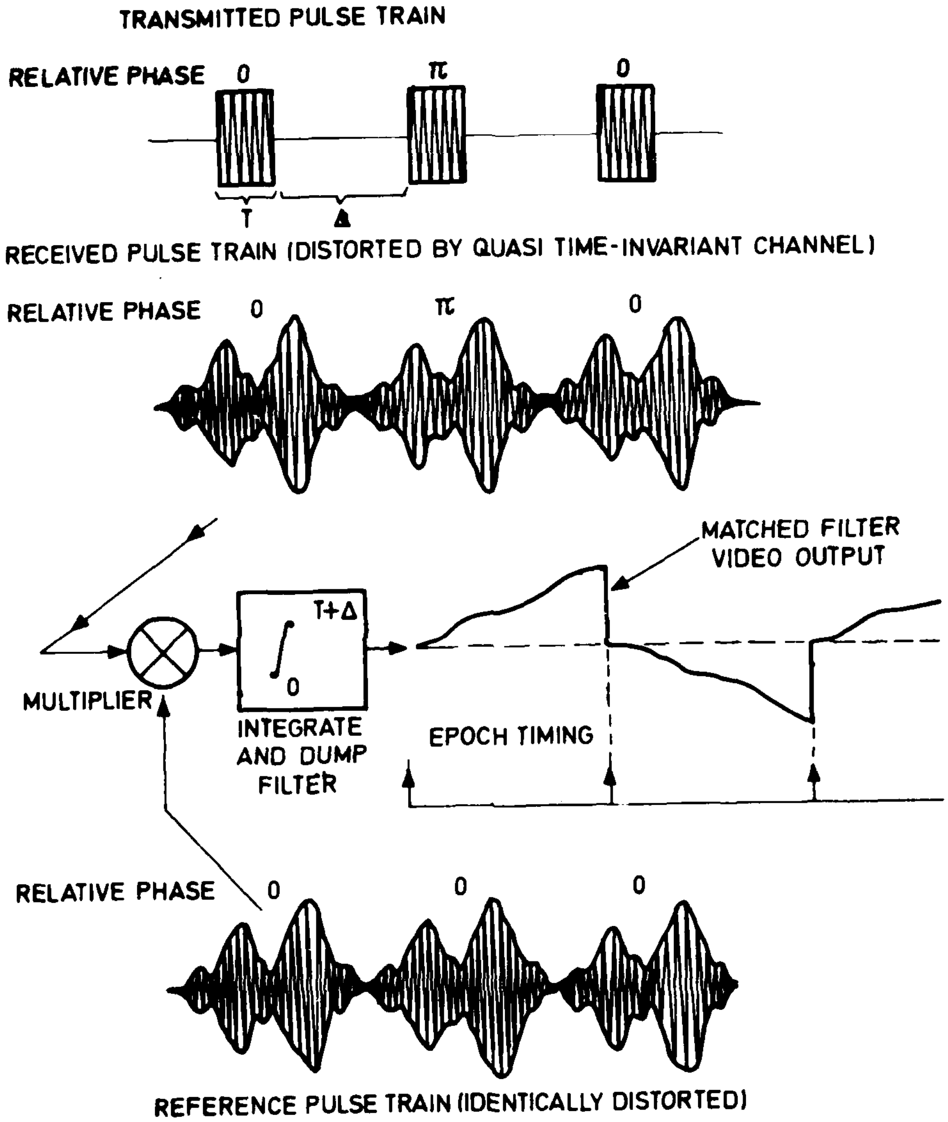


Figure 25. DAR Waveforms (Ideal)

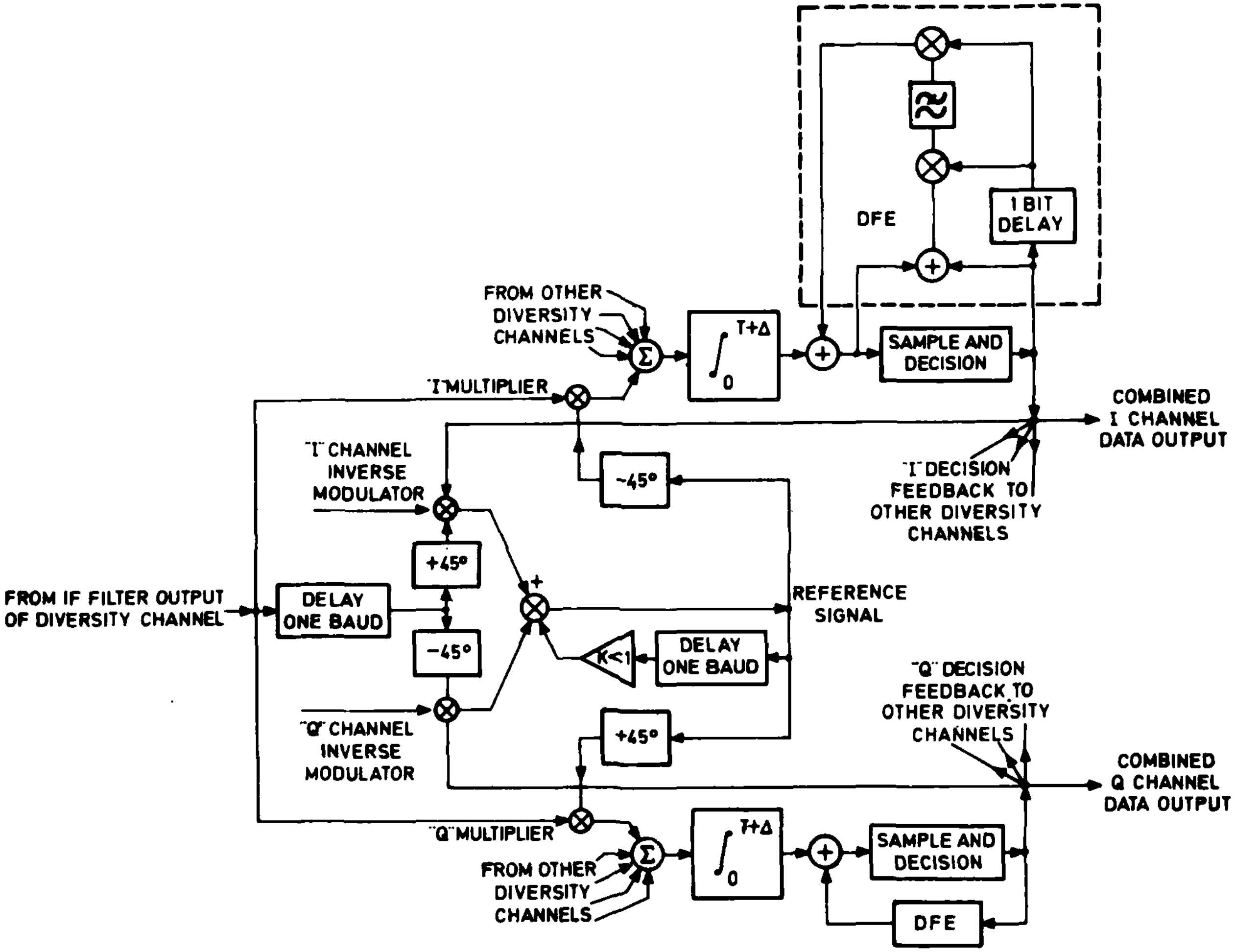


Figure 26. Functional Block Diagram of DAR-IV QPSK Receiver (WITH DFE)

solution to this problem involves the addition to the DAR of a feedback decision feedback equalizer (DFE), similar to that implemented in the ADFE technique discussed earlier. Figure 26 illustrates the application of DFE to the DAR demodulator. As in the ADFE, an error signal is formed from the difference between the analog voltage present upon data detection and the present bit decision (i.e., + or -1). In the absence of intersymbol interference, the error signal will fluctuate about + or -1 (according to the polarity of the transmitted bit) with the standard noise variance. During periods of intersymbol interference, the error signal will demonstrate an increased mean value, depending on the strength of the intersymbol interference and the sign of the previous and present bits. If the previous bit is of the same polarity as the present bit, constructive interference will occur and obscure the development of the error signal. Thus, the error signal must be developed over a period where the effect of an individual bit sense (+ or -1) can be averaged out. The averaged error signal is multiplied by the interfering previous bit amplitude, inverted in polarity, and added to the output of the integrate and dump filter prior to detection. This iterative process will continue until the rms error signal is forced near zero. Through use of the DFE in the DAR, it was hoped to reduce the irreducible bit error rate limit by one and possibly two orders of magnitude for a fixed spectral occupancy and, in many cases, permit a reduction in the duration of the time gate, thus resulting in improved spectral occupancy. However, in a DCS application it is expected that the maximum achievable spectral occupancy will be about 0.7 bits/cycle, with 0.5 bits/cycle more representative of the nominal application.

The performance of the DAR technique as implemented is typified by Figures 27 and 28 which correspond to the same basic test conditions shown in Figures 22-24 for the ADFE. The present DAR with its near optimum utilization of implicit diversity offers a high potential for low and medium rate (1-3 Mb/s) C-Band transmission where the multipath is less extensive relative to an RF symbol length. The development of an optimized DAR configuration, with addition of a workable DFE structure, was aimed at providing a viable transmission alternative for most DCS requirements (including L and S-Band) of 7 Mb/s and less if the necessary RF bandwidth could be obtained (on the order of 10-14 MHz). However, implementation difficulties prevented this expectation from being realized and the DFE augmented DAR is not considered practical.

The intrinsic advantages of the DAR technique are its simplicity in implementation (with obvious cost implications) and its highly efficient utilization of implicit diversity within its design limits. The major disadvantage of the DAR technique results from the bandwidth expansion caused by the transmitter time gating. As mentioned previously, for most DCS applications, transmitter time gating will result in an expected transmission efficiency of about 0.5 bits/cycle. The use of parallel transmission techniques, where a quad diversity system is split to permit parallel dual diversity

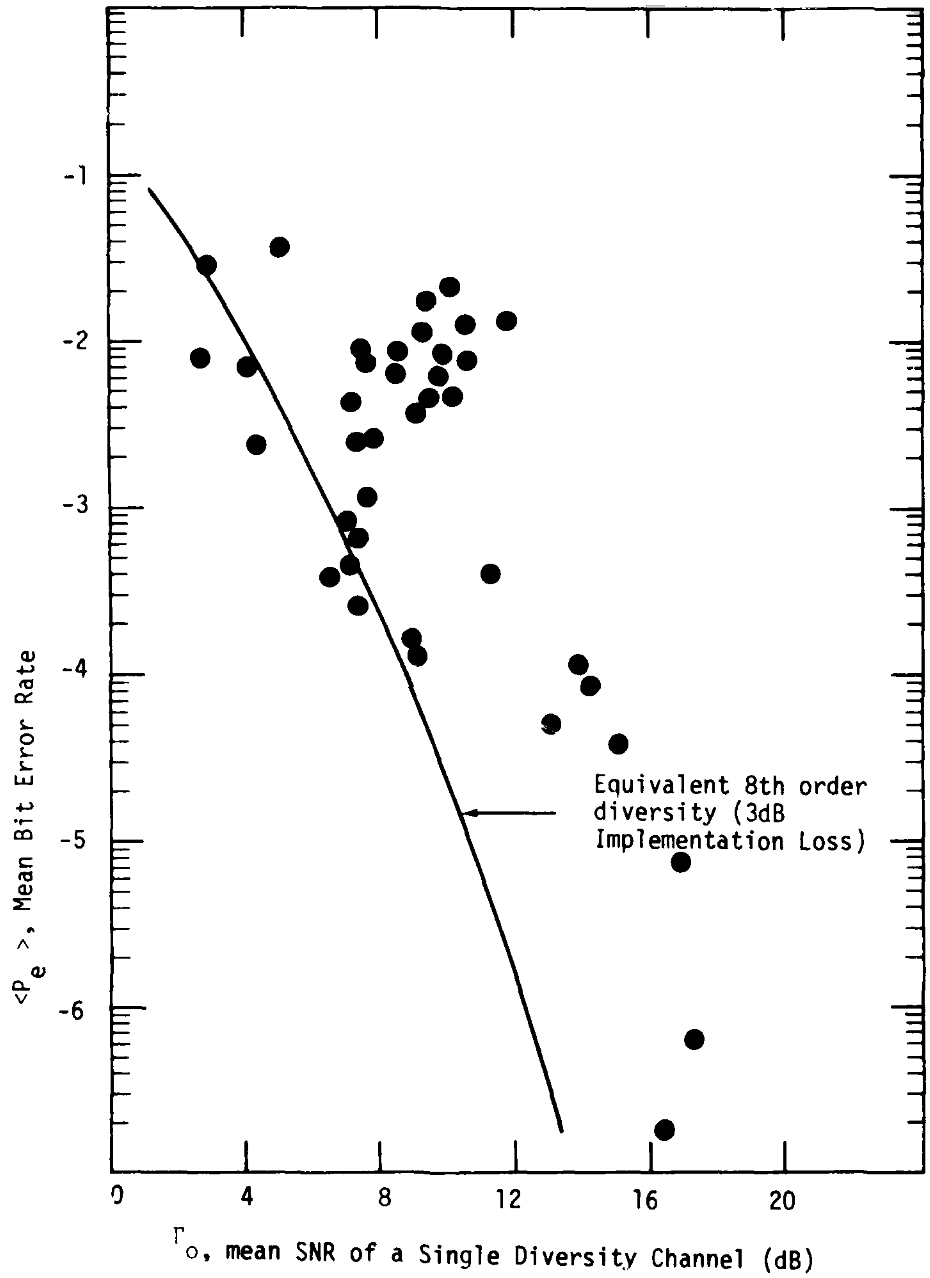


Figure 27. DAR Over-the-Air Performance
Youngstown - Verona (168 miles)
2 dBNF, AN/MRC-98
3.5 Mb/s L-Band, Quad Division

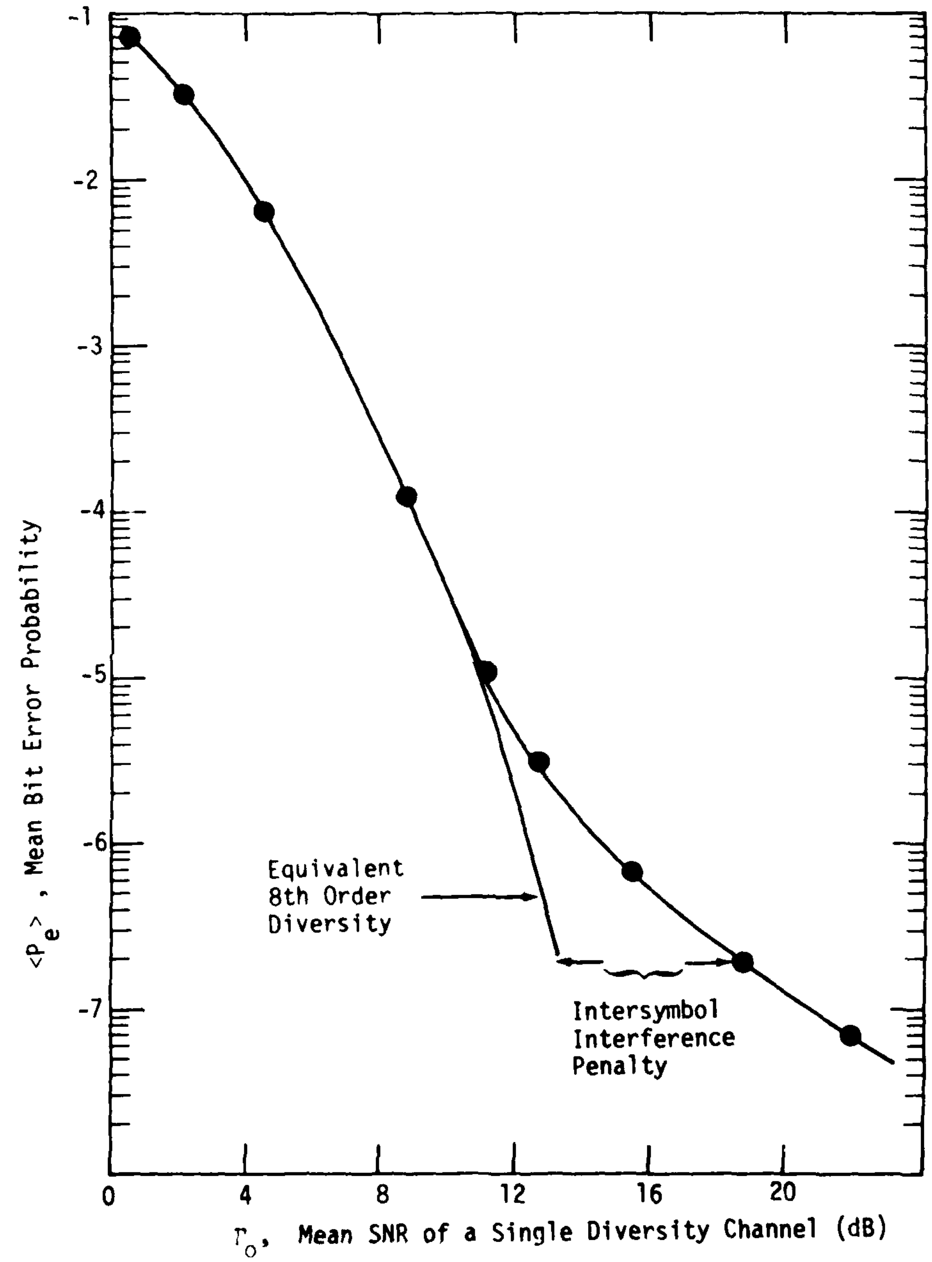


Figure 28. DAR Media Simulator Performance
250 Mile .6° Antenna BW, k=4/3
7.0 Mb/s

transmission at one-half the link throughput (and require one-half the bandwidth) on each dual diversity channel, could alleviate this problem somewhat. However, as noted in section IIIB, the applicability of parallel transmission is far from universal because of its necessary dependence on an extremely favorable link geometry to provide the needed implicit diversity conditions.

Given the parallel development of the DAR and ADFE techniques, they should be considered jointly. Perhaps the most direct comparison of the current ADFE and DAR implementations can be seen in Figure 29. Figure 29 describes the required bit rate SNR necessary to obtain, as an example, an average bit error rate of 1 x 10(-5) as a function of the ratio of rms channel dispersion to transmitted symbol duration, $2\sigma/T$. The quad diversity performances shown for the ADFE and DAR are almost identical until the design limit of the DAR is exceeded. At this point the required SNR increases asymptotically for the DAR, implying the existence of an irreducible average bit error probability worse than 1 x 10(-5) for channels with $2\sigma/T$ greater than 0.5. In dual diversity, the comparison is more dramatic. Here the DAR outperforms the ADFE for all values of $2\sigma/T$ less than 0.5. This is apparently due to its more efficient use of implicit diversity. The ADFE, on the other hand, exhibits a less apparent optimum (i.e., a minimum required SNR) but possesses a significantly enhanced multipath range over which it is capable of operating. In drawing conclusions based on Figure 29, note that there are a number of practical implementation factors which affected the performance summarized in this figure. These are:

- The DAR transmitted bandwidth (99% power BW), while only 1 to 1.25 times that transmitted by the ADFE, is more uniformly occupied (i.e., the 3 dB bandwidth of the DAR is greater than the ADFE). This permits a greater potential for obtaining implicit diversity on a particular path.

- The ADFE forward equalizer structure, as implemented, is fixed at three taps with intertap spacing equal to $T_s/2$. This limits both the implicit diversity obtained and the operating range of multipath delay.

- The DAR coherent reference circuit bandwidth is not optimized, resulting in an unacceptable implementation loss due to bandpass distortion within the demodulator.

- The ADFE performance at dual diversity is hampered by periods of high receive signal level combined with periods of large multipath (i.e., $2\sigma \rightarrow 1.0$). The result is saturation of the IF amplifier/forward equalizer circuitry which can cause error bursts.

Since the time Figure 29 data was taken, the following hardware developments have occured:

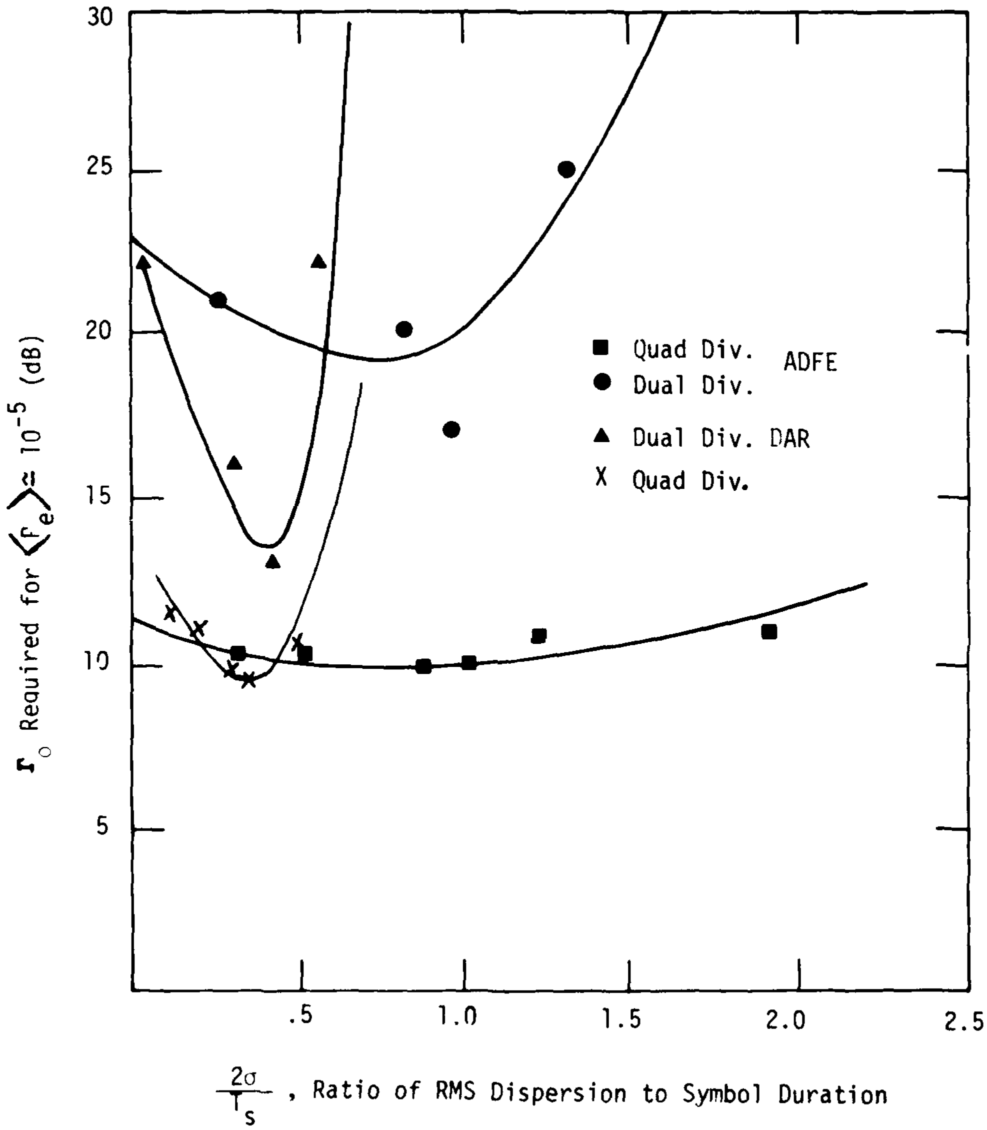


Figure 29. Digital Troposcatter Modem Performance Summary

(1) A new version of the DAR modem as used in the AN/TRC-170(V) series of tactical tri-service digital troposcatter terminals uses a dual interleaved time gated transmitted pulse technique. In this approach two time gated QPSK modulated signals, each at half the mission bit stream data rate and separated slightly in frequency, are combined to yield a transmitted signal with only a small AM component as compared to a single pulse original DAR modem. This technique also increases average transmitted power by nearly 3dB over the original single pulse time gated DAR modem and extends the multipath capability from $2\sigma/T \approx 0.5$ to $2\sigma/T \approx 1.0$. The drawbacks to this approach are an approximate doubling in modem complexity and a small loss in intrinsic diversity gain [15].

(2) Under USA contract DAAB07-79-G-6231 the original engineering model MD-918/GRC modems are being modified to have Digital Radio and Multiplex Acquisition (DRAMA) compatible mission data rates of 3.232, 6.464 and 9.696 Mb/s and hot standby switch capability. Additionally, an improved AFE concept which interchanges the delay and demodulation functions shown in Figure 21 is being implemented. The new equalizer places the demodulator before the tapped delay line. Thus, a digital tapped delay line is used replacing the expensive 70 MHz Surface Acoustic Wave (SAW) delay lines. The new equalizer improves the dynamic range of the modem which reduces the saturation problem noted previously.

Considering these factors, the ultimate results of both the DAR and ADFE development programs clearly support the technological feasibility of digital troposcatter transmission. The key system questions are, can the DAR technique provide the multipath protection required for DCS application, and also can bandwith allocations (i.e., resulting in 0.5 -0.7 bits/cycle) be obtained in the appropriate frequency bands to support optimized application of the DAR? It is apparent from the data presented earlier that long term variations of multipath dispersion of up to twice the yearly median 2σ value (as predicted under nominal refractive conditions) can be expected. The DAR technique is unable to mitigate the estimated range of multipath delay expected on most DCS links over a service year, particularly at the 6.4 and 9.6 Mb/s rates required by DCS digital transmission upgrade plans. Additionally, almost all DCS host nations have raised concerns that the digitization of troposcatter facilities may reduce the bandwidth available for other, co-allocated services such as TV and mobile radio. As an example, the United States, in requesting digital troposcatter bandwidth allocations in the Federal Republic of Germany, was asked to recognize these constraints and ensure that fielded digital equipments make minimum use of the allocated bandwidth consistent with the state of the art. It is clear that given even a 10.5 MHz maximum allocation (which is about seven times the typical current FDM/FM tropo allocation for 48-60 VC's) the DAR modulation format cannot provide the rate/bandwidth efficiency required for DCS-wide application. In addition, the necessity to operate in the UHF

(755-985 MHz) and 1700-2700 MHz bands on longer tropo links critically affects the performance of the DAR technique. As discovered during the combined U.S./NATO Digital Troposcatter Test Program, sufficient RF bandwidth could not be obtained in currently available UHF radio RF equipment to support the DAR time gating approach at a 7 Mb/s data rate.

b. Other Modem Techniques. Other techniques such as the Viterbi algorithm [16] and independent sideband detection [17] have been proposed. However, fabrication of the adaptation circuitry for the Viterbi Algorithm implementation proposed for digital troposcatter, as functionally illustrated in Figure 30, is currently impractical at rates greater than 5 Mb/s. Independent Sideband Detection is relatively inefficient in its use of transmitted power due to the necessity for a complex modulation scheme (PSK/FDM/FM). Studies have indicated that if the Viterbi Algorithm is successfully implemented at high rates, its BER performance should compare favorably with the ADFE technique. However, a disadvantage of the Viterbi code for voice circuits is the delay (50-200msec) experienced by the user.

c. Electronic Countermeasure (ECM) Susceptibility. Recent electromagnetic vulnerability testing of the DAR and MD-918/GRC modems has shown that both are sensitive to typical interferer waveforms [18, 19]. However, the MD-918/GRC because of its robust ADFE signal processing was less vulnerable. The reader is encouraged to review the classified references (18, 19) which contain details and results of the tests including jammer types, the degrees of modem vulnerability in terms of bit error rate and loss of bit count integrity, and recommended design changes to decrease jamming sensitivity. Although the vulnerability testing did not include modem spectrum occupancy variation, this aspect will be included in a future live link test program.

d. Summary. As a result of the aforementioned test and evaluation program, it has been shown that the ADFE technique, as implemented in the MD-918/GRC modem, is superior to the DAR technique for DCS applications. In addition, because of the needed throughput data rates of up to approximately 10 Mb/s with spectrum efficiencies of 1-1.5 b/Hz under multipath conditions of $2\sigma/T \geq 1.0$, it has been judged that the ADFE modem is the only technique in a sufficiently advanced (hardware) state to meet these requirements for DCS upgrades beginning in FY 82.

Although the MD-918/GRC is expected to cost up to 10 percent more than the interleaved pulse DAR modem in equivalent quantities, the difference in link upgrade costs will only be approximately 5 to 10 percent due to the relatively small total modem cost compared to the overall link upgrade costs. A summary of major performance characteristics of the DAR and MD-918/GRC are shown in Table IX.

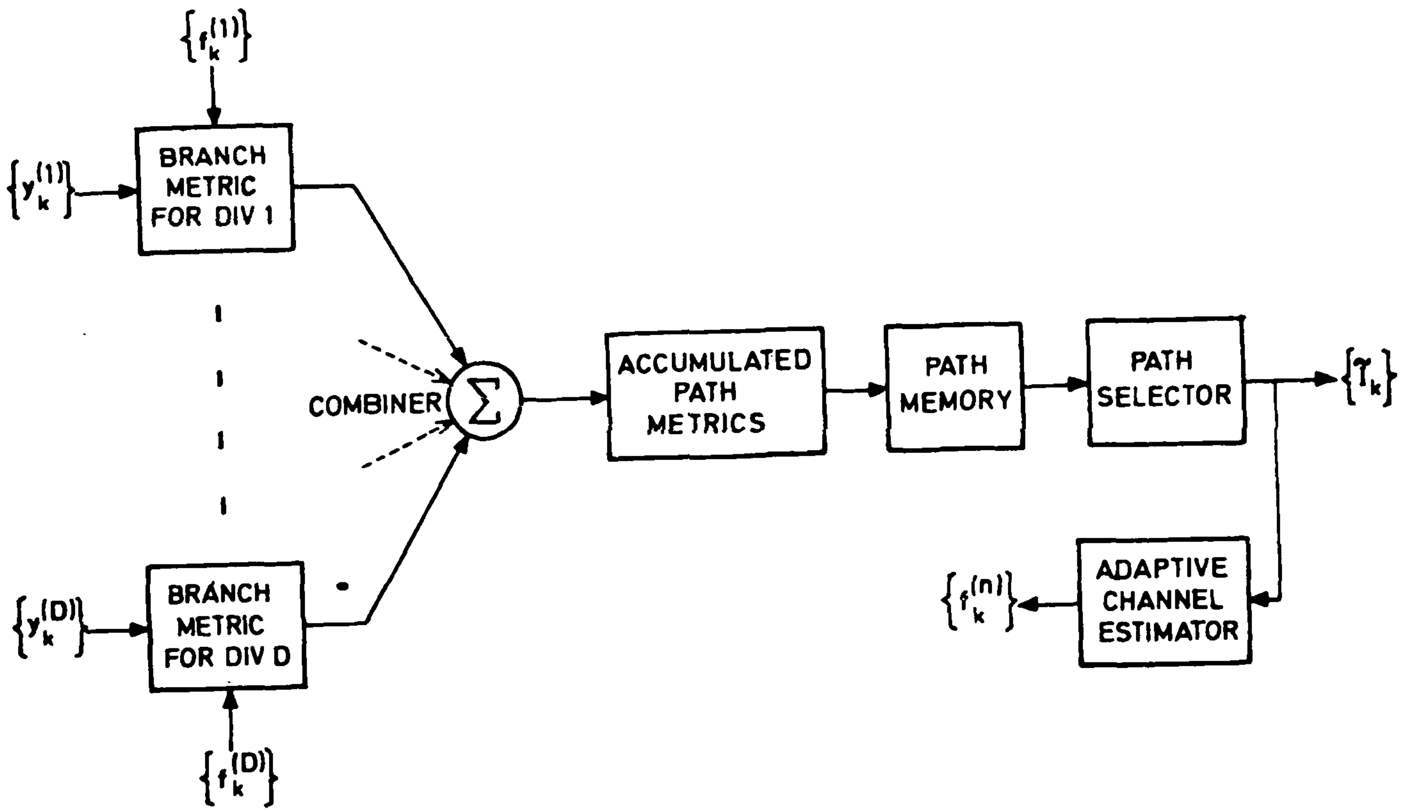


Figure 30. Viterbi Algorithm with Diversity Reception

TABLE IX. COMPARISON OF MD-918/GRC AND DAR MODEM DEMONSTRATED PERFORMANCE

PARAMETER	DAR	MD-918/GRC
BANDWIDTH REQUIREMENT	0.5-0.7 b/Hz	0.92-1.3 b/Hz
DATA RATE	UP TO 7 Mb/s	UP TO 13 Mb/s
MULTIPATH	$0 < 2\sigma/T < 1.0$	$0 < 2\sigma/T < 2.0$
COST	————	UP TO 10% MORE THAN DAR
ECCM CAPABILITY	————	SLIGHTLY LESS VULNERABLE
PLANNED USE	TRI-TAC AN/TRC-170, UP TO 2.3/4.6 Mb/s	ARMY AND AF DEB UPGRADES, UP TO 9.7 Mb/s

Therefore, the ADFE technique is the preferred digital modem to meet the unique DCS requirements for data rate throughput capability, multipath capacity, spectrum efficiency and user-to-user availability.

IV. DIGITAL TROPOSCATTER LINK ENGINEERING

1. BACKGROUND

As seen in Table X, there are four major DCS subscriber types which can influence the design of the DCS digital transmission system. The first, and probably the largest in circuit-miles, is the clear (unenciphered) voice subscriber. As described in DCEC TR 12-76 [1] , the clear voice subscriber will be digitized with Pulse Code Modulation (PCM) at a 64 kb/s rate and time division multiplexed in hierarchical fashion with other subscribers to megabit rates for transmission. As evidenced by Figure 31, the robustness of 64 kb/s PCM allows satisfactory intelligibility at random bit error rates (BER) better than or equal to 1 x 10(-4) over the expected duration of terrestrial fade outages.

TABLE X. MAJOR DCS SUBSCRIBER TYPES

SUBSCRIBER	DIGITAL RATE	FORMAT
Clear Voice	64 kb/s	8 Bit Word
Secure Voice	50 kb/s	6 bit word
Low Speed Data	2.4,4.8,9.6 kb/s	10 bit block
High Speed Data	1.544 Mb/s,3.232 Mb/s, 6.464 Mb/s	10(3) - 10(5) bit block

Many current wideband secure voice requirements are generally satisfied with the DCS digital secure voice system which utilizes 50 kb/s PCM. The performance of this system can be modeled in essentially the same manner as the clear voice PCM subscriber. The future DCS secure voice system will include a configuration using a lower rate digital conversion technique. The future secure voice subscriber will be essentially bit code oriented in nature (as contrasted to the 8 bit PCM word oriented format for clear voice or the 6 bit PCM word oriented format of the 50 kb/s KY-3).

Low speed data systems, such as AUTODIN I, are block formatted and will be initially accommodated via voiceband modems, and eventually accommodated through a combination of digital submultiplexing and modems. These low speed data systems generally provide an internal capability for bit error control through the use of Automatic Repeat Request (ARQ) techniques. Note that the choice of ARQ as the primary error control technique for low speed data systems over conventional Forward Error Correction (FEC) techniques is generally appropriate for slow fading channel applications. This is true because the efficiency of ARQ (and ARQ derived hybrid techniques) is parametrically related only to gross measures of

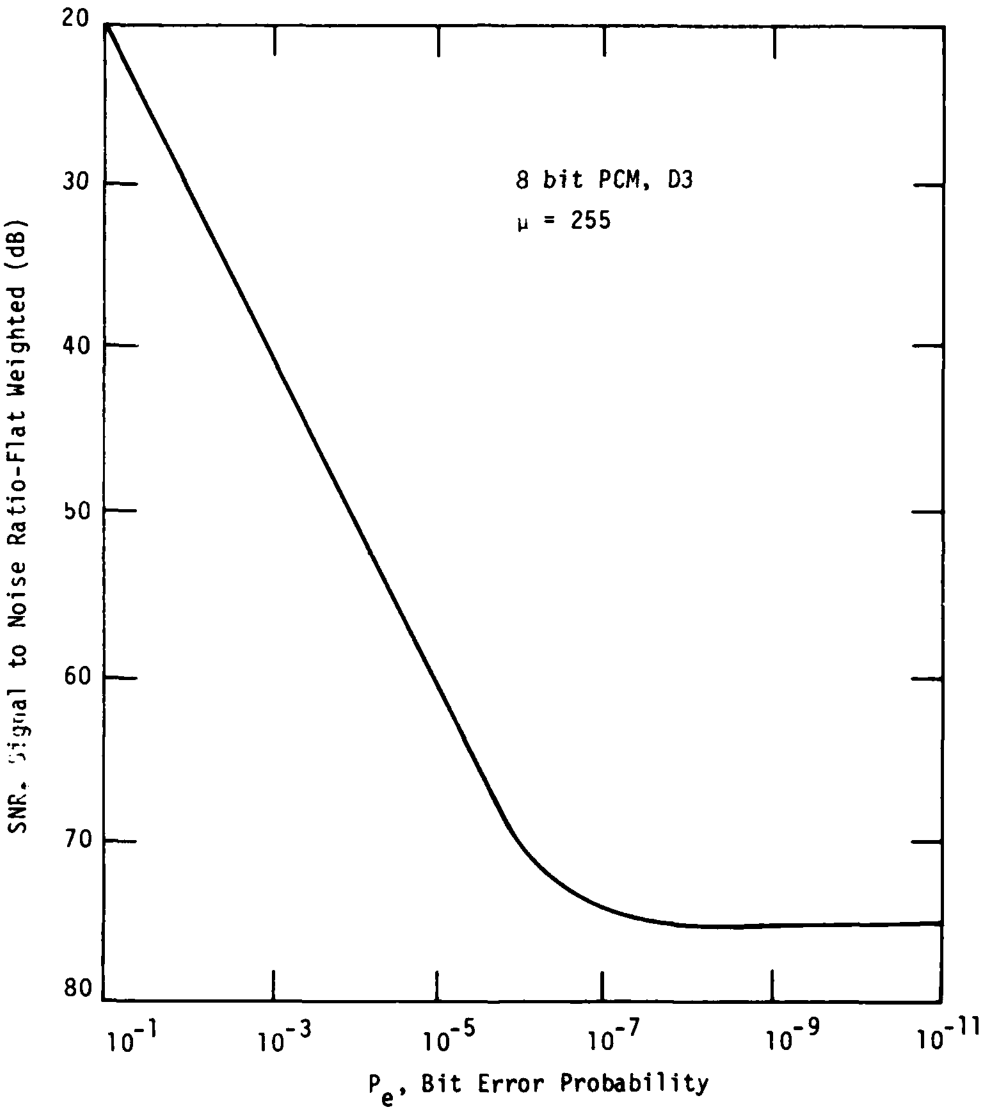


Figure 31. Idle Channel Noise vs Bit Error Probability for PCM

channel quality (block error rate) rather than to the actual distribution of error events (as is the case with FEC techniques). It can be seen that the coding requirements for an effective ARQ data transmission system are much less demanding than those required for FEC, since coding for ARQ requires only error detection (isolation of an error to a particular data block) while coding for FEC requires error correction as well as error detection (to a specific bit in the block). For a terrestrial data connection, where mean fade outage durations are expected to range between 0.5 and 4 seconds (depending on whether tropo or LOS facilities are traversed), the use of FEC techniques to provide equivalent performance to ARQ is likely to require decoded bit storage on the order of a few seconds. For many high speed data systems, this approach is likely to be uneconomical with current technology.

An additional but nevertheless important factor regarding data or record (i.e., message) traffic, is that the overall efficiency of the record system is only partly related to the efficiency of the transmission segment. In fact, other considerations such as message preparation and delivery time are likely to affect the end-to-end performance of a message system more strongly. Thus, the seemingly major deficiency of having the ARQ data system run at 70-75 percent maximum throughput due to a high incidence of block retransmission requests, is actually less serious when one considers the typical message delivery times currently associated with AUTODIN I.

Clearly, this discussion presents only a heuristic treatment of low speed data system performance over a terrestrial transmission system. Nevertheless, the perspective related above is useful. In the overall design of a data system, other factors beside propagation path quality (within broad limits) will generally determine the grade of service provided by the terrestrial network to a data customer. In general, the potential degradation of data service due to blocking probabilities (in a switched data system) and lengthy message preparation and delivery times will be dominant. Thus, expending additional resources on the transmission plant to improve quality beyond a level acceptable for voice appears questionable without other improvements.

The introduction of satellite communications links into a long haul data connection introduces a significant return path delay (for ARQ acknowledgement) and a noisy channel which is essentially nonfading. For the satellite link alone, FEC systems are expected to perform better than most continuous ARQ techniques since random errors are likely to dominate the performance of the nonfading satellite link. However, on an overall systems basis in which combined satellite and terrestrial transmission media are traversed, ARQ is likely to continue to be the major end-to-end error control technique with FEC used on a bulk (multichannel) basis over the satellite transmission link to provide an additional satellite link power margin. For efficiency, the ARQ low rate return channels for a number of data users can be submultiplexed at appropriate concentration points with other low speed digital signals for transmission and distribution to the originators. This action avoids the necessity for high-rate full-duplex service solely to provide a return path for data block acknowledgement.

From the foregoing discussion, it is evident that low speed data systems of the type used in AUTODIN may actually be less demanding of continuous channel quality than voice, particularly since reasonable efficiency can be obtained under channel conditions which would be disruptive to the PCM voice user (e.g., a continuous BER of worse than 10(-4)). To support this observation, a quantitative treatment of low speed data system performance is given later in this section which considers the performance of block formatted data systems as related to the concept of error free block probability. The concept of error free block probability is appropriate since it identifies a lower bound for both ARQ and FEC data system performance and thus enables a subscriber to decide whether error correction techniques are actually required on a particular system.

The channel quality requirements for high speed data and imagery systems (1.544 Mb/s and greater) are currently under development. However, it is expected that these systems will also be block or frame oriented with perhaps somewhat longer block lengths than the low speed data systems. As shown later in this section, the performance of high speed data systems, employing block lengths of 10(3) bits or less, is not expected to be the dominant influence in the choice of troposcatter link design requirements. The expected performance of high speed data systems could be further improved through the use of the ARQ techniques similar to those employed with low speed data. A potential deficiency of ARQ in high speed data applications is the absence of a real time, interactive capability of an ARQ implemented system, which results primarily from the time delay associated with data block retransmission actions. However, it is expected that the end instruments of the high speed data system will remain analog, often with a human interface. Requirements for real time information transfer may actually be satisfied by near-real-time data transfer using ARQ or Hybrid ARQ (ARQ together with FEC) methods, even where extensive satellite transmission is involved. The exclusive use of FEC techniques to provide high speed data system error control on DCS LOS and troposcatter systems is not likely to be feasible in the near and mid-term because of the storage requirements necessary to reduce degradations resulting from relatively long terrestrial channel fades by data interleaving.

The preceding discussion implies the dominance of voice quality objectives in the development of digital troposcatter link design requirements. Relative performance characterizations of voice and data transmission are provided herein to demonstrate this dominance.

The ensuing development of digital troposcatter link performance characteristics will be outage oriented rather than oriented towards more conventional characteristics such as an average bit error probability, P_e. This characterization is particularly appropriate and desirable for fading channels such as troposcatter and LOS where the "instantaneous" SNR observed at the nominal link operating state (i.e., under median propagation conditions) can be on the order of 30-40 dB greater than when the link is deeply faded. In addition, the percentage of time during which deep fading actually occurs will be quite small for links designed with adequate system gain and diversity transmission. Since average channel characterizations such as P_e do not directly reflect this behavior, they cannot provide the insight necessary for the development of effective system design criteria.

However, given knowledge as to the bit error distribution for a fading channel such as troposcatter, this channel can be characterized from a digital viewpoint (as an example, the probability that a specific threshold bit error probability, p_e, will be exceeded as a function of the average SNR). Thus, it is possible to characterize the behavior of the troposcatter channel in a more user-relevant form which can still be based on certain easily measurable channel statistics such as received signal level and order of diversity. Based on this concept and identification of the performance thresholds for various DCS subscriber types, a digital troposcatter link performance characterization will be developed which can be directly related to the PCM voice user through the concept of outage probability and, for the data subscriber through the concept of error free block probability.

In the design of DCS digital transmission links, various "fade outage ranges" and corresponding "fade outage probabilities" have previously been proposed in DCEC TR 12-76 for the clear voice subscriber. In DCEC TR 12-76, a fade outage was defined as an interval in which the bit error probability is equal to or worse than 10(-4). To understand this definition, it must be recognized that the actual determination of a 64 kb/s PCM outage threshold for a fading channel is much more difficult than merely calculating the probability of an error in the most significant bit of a PCM word (i.e., an event which could cause a speech significant disruption) under random bit error rate conditions. Due to the temporal fading statistics of the troposcatter channel, a 10(-4) threshold bit error probability, Pe, for 64 kb/s PCM may actually be conservative, since diversity troposcatter link fades below a P_e = 10(-4) will generally last less than a second, and therefore the probability of an audible speech disruption is expected to be rather low. Thus an argument can be advanced which, given knowledge of the expected value of P where the first PCM error occurs, would set the speech outage threshold at an error probability greater (i.e., worse) than 10(-4) . However, the use of a bit error probability of 10(-4) as an outage threshold is certainly more accurate than grossly specifying a Pe of 10(-4) (as previously required in the design of digital DCS LOS links) and, for the power and bandwidth limited troposcatter channel, significantly less costly. Therefore, in the absence of data on the performance of PCM over troposcatter links, an outage threshold bit error probability of 10(-4) will be used.

In the following paragraphs, the expected fade outage statistics (e.g., fade outage rate and fade outage duration) are modeled for diversity troposcatter transmission. The fade outage criteria developed in reference [1] are used to define user quality requirements against which the DCS troposcatter link design criteria are set. These criteria are given in Table XI for reader convenience. After this has been completed, the concept of service probability or confidence factor is examined in light of its potential effect on troposcatter link design requirements. This discussion provides a detailed rationale for requiring a specific service probability in the design of DCS digital troposcatter links.

TABLE XI. DCS PCM VOICE PERFORMANCE CHARACTERISTICS

FADE OUTAGE RANGE (i)	FADE OUTAGE CRITERIA	FADE OUTAGE PROBABILITY (Pi)*
1	0.2 sec ≤ outage < 5 sec	7.5 x 10(-4)
2	5 sec ≤ outage < 1 min	7.5 x 10(-5)
3	2 < outages/min ≤ 5	2.5 x 10(-3)
4	outages/min > 5	1 x 10(-4)

*Pi expressed as a percentage for reader convenience

2. LINK DESIGN CRITERIA

Historically, the overall performance of FDM/FM troposcatter links was related to the percentage of time that a particular short term (e.g., over 15 min) average SNR could be sustained out of the long term distribution of short term SNR's. This percentage of time was interpreted as a time availability. A variation of this convention is used here.

Specifically, DCS troposcatter link design objectives are formatted in terms of a specified short term SNR which must be exceeded all but a certain percentage of time for quadruple diversity transmission configuration. For this configuration, candidate outage thresholds will be proposed for each of the four outage ranges listed in Table XI and will be expressed as short term SNR's, γ_i , where i represents one of the four outage ranges of Table XI. Continuous operation at these threshold SNR's results in a high probability that each outage range associated with the particular threshold SNR is experienced on a recurring basis.

Based on this representation, the outage probabilities (similar to media unavailabilities) listed in Table XI as Pi which accompany each of these outage ranges will be assumed to be met if the short term mean SNR, γ_o , on an arbitrary troposcatter link exceeds the appropriate γ_r all but P_i percent of the time, where P_i is the outage probability (in percentage form) associated with the ith outage range. In general, since there are four outage criteria, this process results in four candidate link design criteria for each link. For each link, the most demanding (in the long term sense) of the resultant four (P_i ,γ_i) pairs is chosen as the dominant troposcatter link engineering criterion for that link. Requirements for system gain, transmitter power, antenna size, and other parameters can be determined from the dominant criteria in a straightforward manner.

Key to the determination of the criteria which represent the most demanding link design requirements is an analysis of the long term troposcatter fading distribution. This distribution represents the expected variability of γ_o over an operating year. The slope of the long term γ_o distribution denoted by its standard deviation, σ , determines which fade outage range and associated outage probability actually require the most stringent link design. A short mathematical overview of this approach is presented below as before, for deriving link design requirements for a typical DCS link.

In general, the mean probability of experiencing a particular fade outage range, i, can be expressed as

$$P_i = \int_{\infty}^{\gamma_r^i} P(i|\gamma_o)\, P(\gamma_o)\, d\gamma_o \tag{11}$$

where P_i = Mean probability of experiencing the ith fade outage range

$P(i|\gamma)$ = Probability of occurrence of the ith fade outage range given a particular short term SNR

$P(\gamma)$ = Probability density function describing the long term variation of the short term mean SNR

γ_r^i = The value of γ_o where $P(i/\gamma_o)$ is essentially unity.

As is shown subsequently, $P(i|\gamma_o)$ is an extremely steep function of γ_o for diversity troposcatter channels. Therefore,

P_i will be essentially determined by periods of time when γ_o is small. Equation (11) is generally very complex to evaluate since joint statistics of SNR and multipath dispersion must be considered. A computer program has been developed by the U.S. Army under DCEC auspicies which evaluates this expression on a numerical basis. To facilitate understanding of the computational method, an approximate method is used to derive link design requirements for a hypothetical troposcatter link of typical parameters. Because of the rapid variation of $P(i/\gamma_o)$ with γ_o, an appropriate approximation is

$$P_i \simeq P(i/\gamma_T^i)\left[P(\gamma \leq \gamma_T^i)\right]. \tag{12}$$

P_i and $P(i/\gamma_T^i)$ are as defined previously and $P(\gamma_o \leq \gamma_T^i)$ is the probability that the short term SNR, γ_o, is equal to or less than some γ_T^i.

Also described previously, values of γ_o are chosen to make $P(i/\gamma_o) = 1$. Thus

$$P_i \simeq P(\gamma_o \leq \gamma_T^i) \tag{13}$$

where γ_T^i are the threshold values of γ_o which result in $P(i/\gamma_o) \simeq 1$.

Finally then, by the above model, $P(\gamma_o \leq \gamma_T^i)$ is simply the fade outage probability associated with the ith outage range.

Beginning the detailed development of link design criteria, it is seen that P_o, or the short term probability that an outage will be experienced (i.e., a probability of bit error rate equal to or worse than 10(-4) given a particular short term SNR) on a diversity troposcatter link, can be estimated via the method developed by Osterholz and Smith [20]. For a quad diversity link, P_o can thus be expressed for a particular γ_o as

$$(P_o/\gamma_o) = 1 - b\sum_{k=1}^{m} \frac{\ell^{(k-1)}}{(k-1)!} \tag{14}$$

where (P_o/γ_o) = Probability of a fade outage given a short term SNR, γ_o

- b = $(2 \times 10(-4))^{2/\gamma_o}$
- ℓ = -ln(b)
- γ_o = Short term SNR (Actual Ratio, not in dB)
- m = $4n_i$ (quad diversity).

The fade outage performance, as expressed by (14), is assumed to have a second order (n_i =2) implicit diversity enhancement. This means that one over the information rate is greater than the rms multipath dispersion but less than twice the rms multipath. This assumption is considered reasonable for many DCS troposcatter paths. Figure 32 illustrates the behavior of equation (14) for quad diversity digital troposcatter link configurations as a function of γ_o. For comparison purposes, measured fade outage data are provided along with the calculated curve. These data were taken on a 187 mi (301 km) C-Band link at a nominal data rate of 9.4 Mb/s.

Having characterized fade outage probability in the cummulative sense, the expected temporal distribution of these outages is now examined. Again using the expressions developed in reference [20], conditional mean outage frequency and duration statistics can be expressed for diversity troposcatter transmission as:

- o Mean Outage Rate, η_o

$$(\eta_o|\gamma_o) = 2.4m\,N\ell^{1/2}\left[1 - \frac{b\sum \frac{\ell^{(k-1)}}{(k-1)!}}{1-b}\right] \tag{15}$$

where ℓ, b and m are as defined previously and N is defined as the mean channel fade rate in Hz. Equivalently, the Mean Time Between Fade Outage (MTBFO) or the mean interarrival time of outages can be expressed as $1/\eta_o$.

Further, knowing MTBFO and $(P_o|\gamma_o)$, the mean duration of an outage, τ_o can be expressed as

- o Mean Outage Duration

$$(\tau_o|\gamma_o) = (P_o|\gamma_o)\cdot MTBFO \tag{16}$$

The distribution of fades relative to the mean can be determined from assumptions of a narrow band Rayleigh process and expressed as

$$P(\tau) = \frac{2}{u}\,I_1\left(\frac{2}{\pi u^2}\right) EXP\left[-\frac{2}{\pi u^2}\right] \tag{17}$$

where $u = \tau/\tau_o$, I_1 is the modified Bessel function of the first order, and P(t) is the probability that an outage will have a duration of t seconds or less. Figures 33 through 35 illustrate the relationship of η_o, t_o and P(t) to γ_o for diversity digital troposcatter transmission.

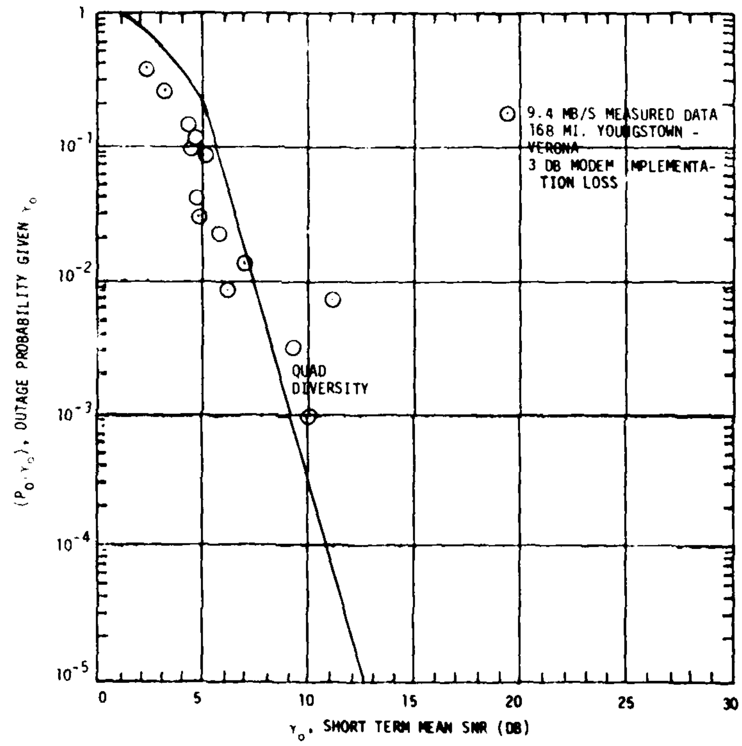


Figure 32. Troposcatter RF Link Outage Probability

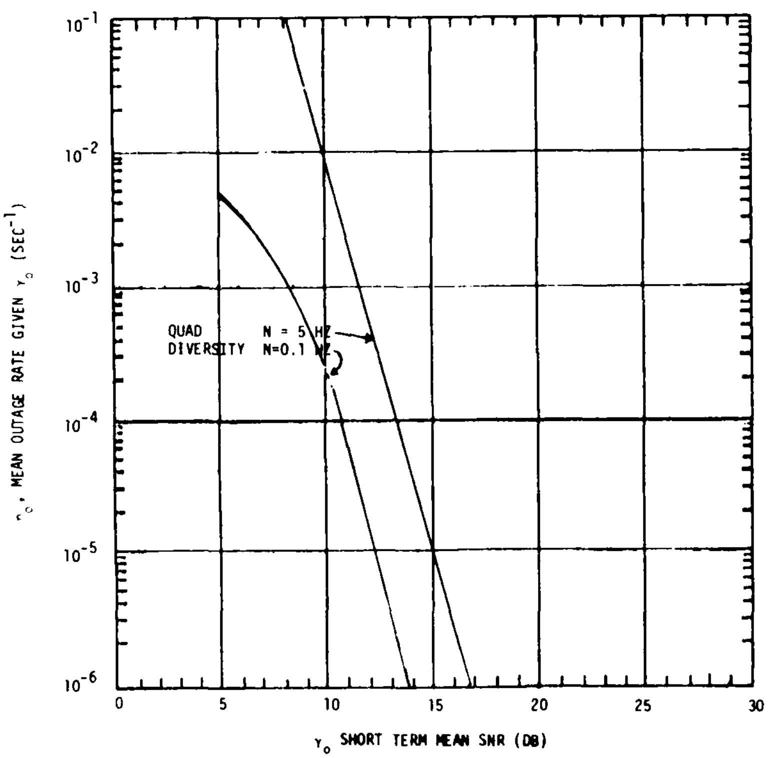


Figure 33. Troposcatter Link Outage Rate

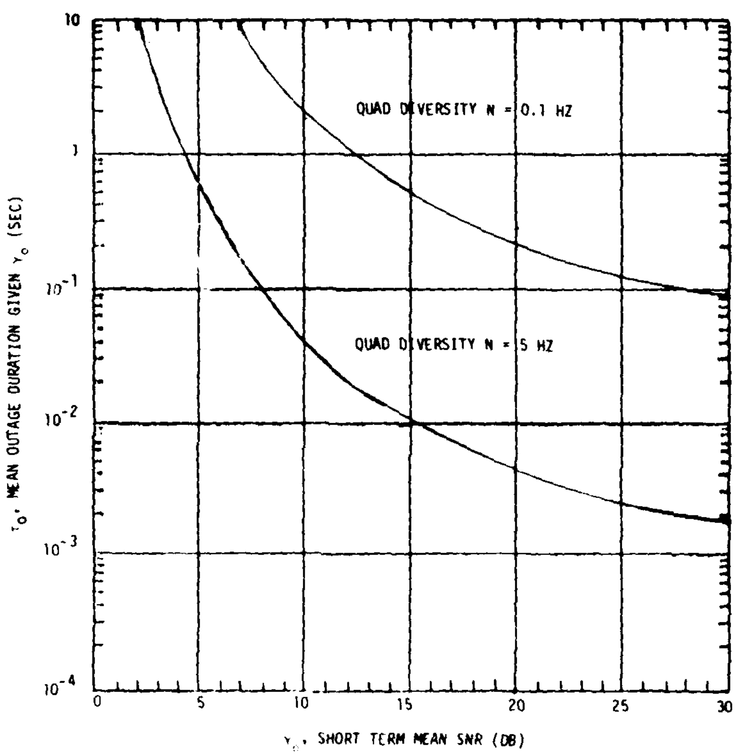


Figure 34. Troposcatter Link Outage Duration

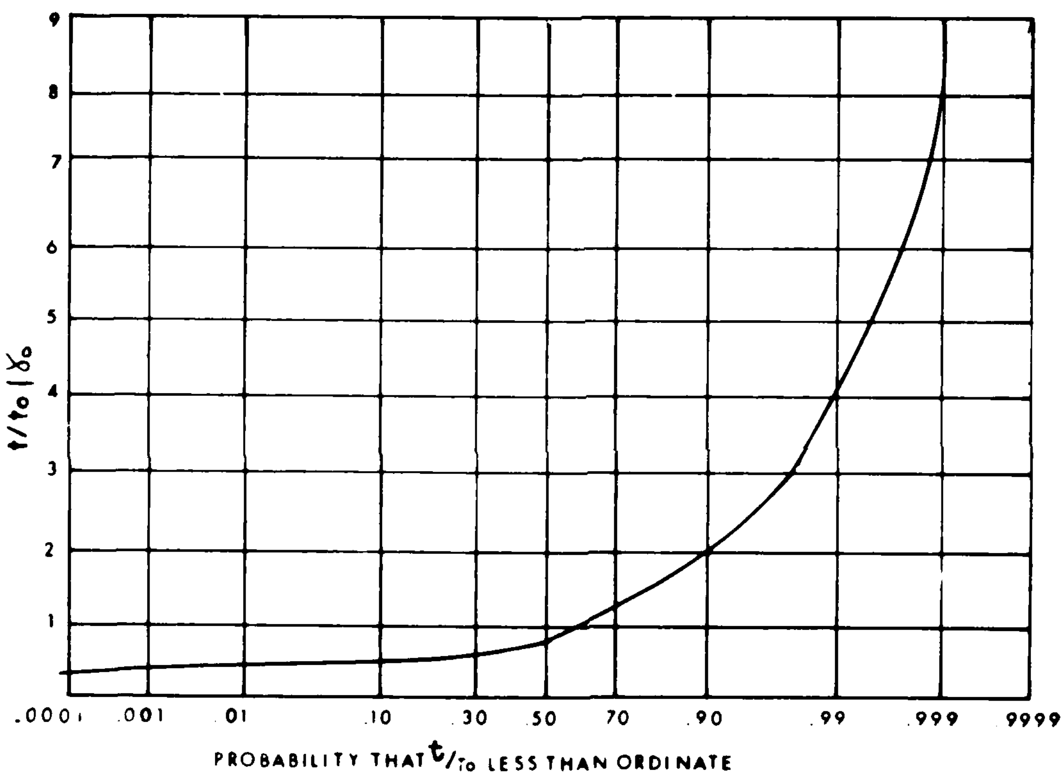


Figure 35. Distribution of Troposcatter Hop Outage Duration

The information in Figure 33 implies that Mean Time Between Fade Outages (MTBFO with duration $t_1 \leq t_o \leq t_2$) can be estimated by calculating

$$\left(MTBFO[T_1,T_2] \mid \gamma_o\right) = \frac{(MTBFO \mid \gamma_o)}{P(T_2) - P(T_1)} . \tag{18}$$

The scaling of MTBFO (t_1, t_2) to give an estimate of the number of outages that will occur during a call minute is simply $60/MTBFO[T_1, T_2]$.

The above discussion leads to an expression for the relationship between γ_o and the probability of fade outage per call minute. This expression determines the γ_T^i at which operation results in a near unity probability of experiencing the first and second outage ranges of Table XI (i.e., P_1, P_2). In addition, under certain conditions of γ_o and mean fade rate, the troposcatter channel is expected to fade rapidly enough to cause several fade outages during a call minute; hence the third and fourth requirements in Table XI are necessary. The probability that between two and five fade outages will occur during a minute and the probability that more than five fade outages will occur during a minute can be estimated from equation (15) by determining the values of γ_o for which

$$\frac{2}{60} < \eta_o < \frac{5}{60} \quad \text{AND} \quad \eta_o \geq \frac{5}{60} . \tag{19}$$

Link operation at or below these values of γ_o denoted as γ_T^3 and γ_T^4 results in a near unity probability that outage ranges 3 and 4 will be experienced on a recurring basis.

The association of a particular γ_T^i with its appropriate P_i (to be written: (γ_T^i , P_i)) as shown in Table XII will then constitute a candidate link design requirement. The determination of which of the (γ_T^i, P_i) pairs in fact represents the most stringest link design requirement can only be accomplished by considering the long term distribution of short term SNR's typical of DCS troposcatter paths. The objective of the ensuing analysis is to determine, for each transmission configuration, which of the candidate link design requirements listed in Table XII requires the highest long term SNR.

TABLE XII. CANDIDATE LINK REQUIREMENTS
(HYPOTHETICAL LINK)

FREQ BAND	DIVERSITY	γ_o (dB) > ALL BUT Pi OF THE TIME			
		i=2	i=3	i=4	i=5
		10	5	4	N/A
L,S,C	QUAD	P2=(0.075)	P3=(0.0075)	P4=(0.25)	P5=(0.01)

P_i is expressed as a percentage
γ_o is expressed in dB
i is defined as outage range

As outlined earlier, outage probabilities in the outage ranges identified in Table XI necessitate link design that insures that a specific short term mean SNR, γ_T^i, is exceeded all but P_i, where P_i is the outage probability associated with the i_{TH} outage range.

Determination of the most demanding of the (γ_T^i, P_i) pairs listed in Table XII is begun by considering the long term distribution of short term SNR typical of the troposcatter channel. This long term distribution is usually described as being log normal. That is,

$$P(\gamma_o < \gamma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(\gamma_o-\gamma)^2}{2\sigma^2}\right] \quad (20)$$

where $P(\gamma_o < \gamma)$ is the probability that the mean SNR is less than γ_o, γ_o is an arbitrary short term SNR (hourly mean) in dB, γ is the long term (i.e., yearly) SNR in dB, and σ is the standard deviation of γ_o about γ, also in dB. The standard deviation of the distribution, σ, is roughly indicative of the expected rate of change of the short term SNR over time. As shown in Figure 36, most DCS links are expected to exhibit standard deviations on the order of 4-8 dB. In general, the shorter links will exhibit higher observed standard deviations. Since most DCS troposcatter paths are less than 300 miles (480 km) in length, large measured standard deviations are not surprising. As an example, Figure 37 is a distribution of γ_o derived from measured received signal level data for a typical medium distance DCS troposcatter link [21]. Values were calculated in a 6.464 Mb/s bit rate bandwidth (96 equivalent VF channels).

From observations of the slope of the long term distribution of γ_o for this typical link as evidenced by σ = 6 dB in Figure 37, the expected range of γ for DCS troposcatter paths and the typical link design requirements (Table XIII), it is obvious that the most demanding link design requirements are represented by the outage range number two. Based on this analysis, the hypothetical digital troposcatter link requirement is presented in Table XIII and denoted as (γ_R, P_R).

TABLE XIII. DCS LINK DESIGN REQUIREMENTS FOR A TYPICAL DIGITAL TROPOSCATTER LINK

BAND	DIVERSITY	LINK DIVERSITY REQUIREMENT(γ_R, P_R)*
L, S, C	QUAD	(10, .075)

*P_R expressed as a percentage
expressed in dB

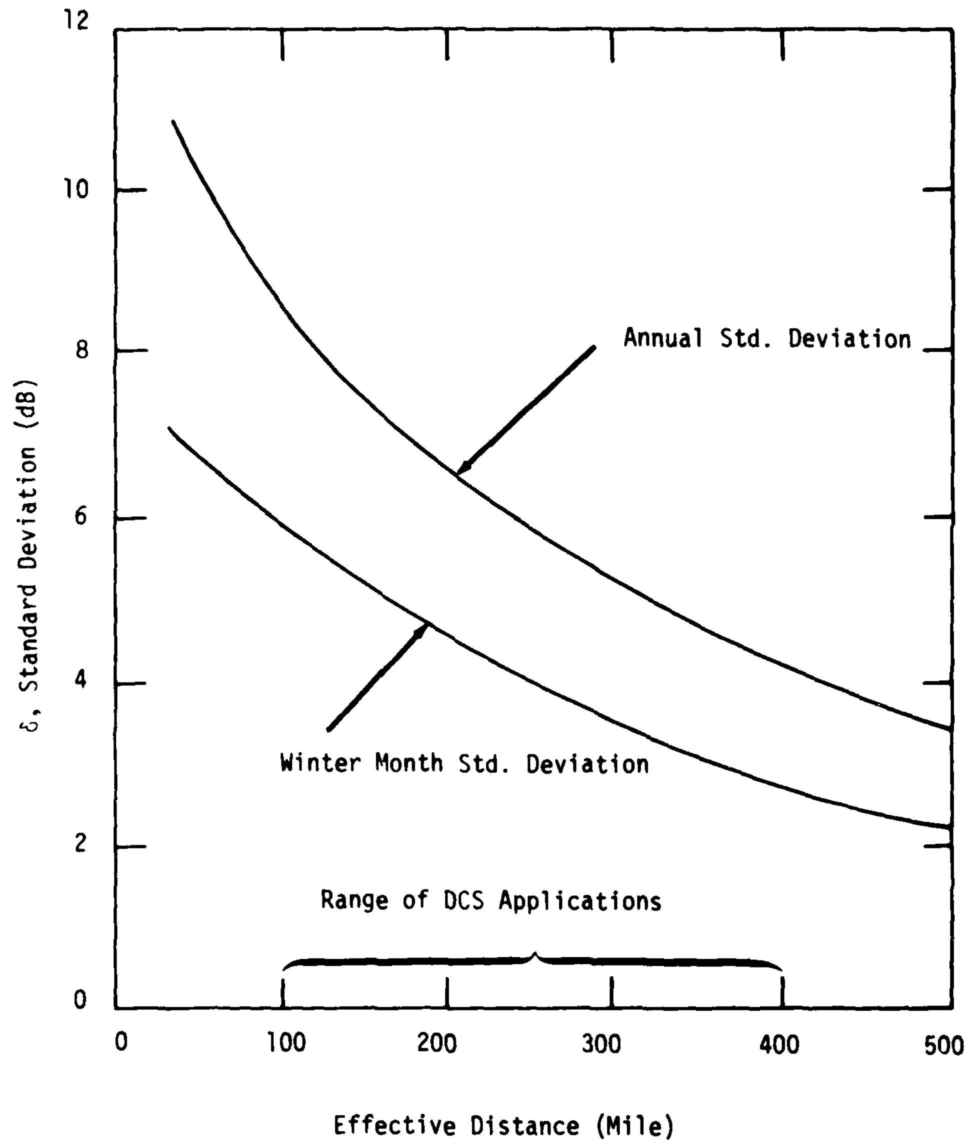


Figure 36. Standard Deviation of Path Loss vs Effective (Angular) Distance

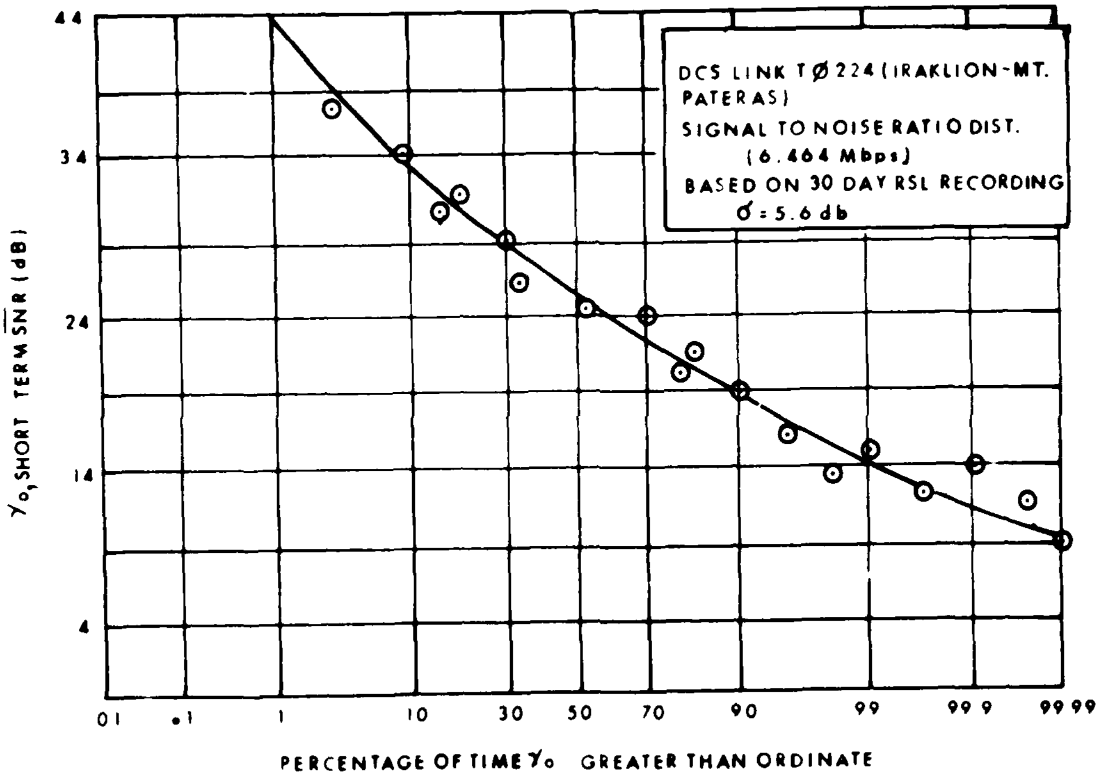


Figure 37. Long Term Distribution of γ_o for a Typical DCS Troposcatter Hop

(Note: The above requirement was derived for a hypothetical link. Tropo link design will remain a link by link task and will vary from the above criteria on occasion).

The tandeming of troposcatter links should not appreciably degrade the performance of the transmission system as a whole since the worst case effect (i.e., correlated long term fading on the tandemed links) will linearly decrease the interarrival time of outages with the outage duration statistics remaining essentially unchanged. For links with uncorrelated long term fading (or tandem connections extending over large areas), the overall outage statistics are likely to be almost totally determined by the link with the lowest γ_o (or the links with the highest long term fading correlation) at any time. Perhaps more directly, it should be pointed out that the original probabilities specified in reference [1] and repeated in Table XI were, in fact, allocated on a mileage basis. Thus, whether the 600 mile DCS reference channel described in reference [1] is made up of all LOS, all troposcatter or a mix of terrestrial media, the overall channel quality should remain within specification.

3. ERROR FREE BLOCK PROBABILITY

The concept of error-free block probability attempts to provide a subscriber with an indication of the expected transmission efficiency of his data circuit. In general, for a link designed to provide a particular γ_o (short term SNR), the probability of receiving a data block of n bits in duration with at least one error can be estimated with the assumption that bit errors and block errors are approximately related by

$$P(\text{block error}) \simeq n_i \cdot P(\text{bit error}). \tag{21}$$

Adapting expression (15), the probability of receiving a 10(3) bit block with at least one error can be written as

$$P(BE|\gamma_o) = 1 - b_\beta \sum \frac{l^{(k-1)}}{(k-1)!} \tag{22}$$

where $P(BE|\gamma_o)$ = Probability of receiving a block in error given

$$b_\beta = (2 \times 10^3)^{2/\gamma_o}$$
$$l = \ln(b_\beta)$$
$$m = n_i \cdot n_c .$$

As noted earlier, the long term performance of most DCS troposcatter links is accurately described in terms of a log normal distribution of γ_o, having a standard deviation on the order of 4-8 dB. Based on this description, it is expected that block error probabilities will be distributed similarly, with the overall probability (i.e., on a long term basis) of a block error heavily influenced by periods of large, long-term path loss (e.g., during the late afternoon hours). The mean long term probability of receiving a data block in error is then formulated in the same manner as the PCM voice outage analysis developed earlier. That is,

$$P(BE) \simeq P(BE|\gamma_R^T)\, P(\gamma \leq \gamma_R^T) \simeq P(BE|\gamma_R^T) \cdot P_R \, . \qquad (23)$$

For a data block of 10(3) bits, Figure 38 illustrates the distribution of $P(BE|\gamma_o)$. As specified in reference [1], the probability of receiving a 10(3) bit block in error for the reference troposcatter hop must be no greater than 2.5 x 10(-3). The link design requirements listed in Table XIII, which were derived on the basis of PCM speech quality considerations, will permit the achievement of a $P(BE|\gamma_o) \cdot P_R$ which is less than 2.5 x 10(-3) that a 10(3) bit data block will contain one or more errors due to a media caused outage. Therefore, DCS PCM speech quality requirements are seen to require the most demanding link design.

4. SERVICE PROBABILITY

The concept of service probability and its impact on digital troposcatter system link design are discussed in the following paragraphs. Because of demonstratedly significant variability of the long term performance of identically sited and configured troposcatter links, the concept of service probability (essentially a link design confidence factor) was developed by the National Bureau of Standards (NBS) [5]. As an example, a troposcatter link design with a service probability of 0.5 implies that out of 100 identically configured and sited links, 50 links are likely to meet or exceed the link design requirements.

In an attempt to achieve reliable transmission link performance in the DCS, analog troposcatter links were generally engineered to provide long term performance at service probabilities of 0.85 to 0.95, depending on the function of the link (e.g., a tail or backbone). Unfortunately, significant incremental costs in the form of additional required system gain resulted from link designs at these service probabilities, and thus a number of analog DCS troposcatter links were actually installed at lower service probabilities (e.g., 0.5). Because many of these links are being considered for upgrade and digitization, it is then useful to reexamine the sensitivity of system gain to variations in service probability for digital links. Figure 39 illustrates this sensitivity and shows the incremental system gain necessary to meet, for a medium distance

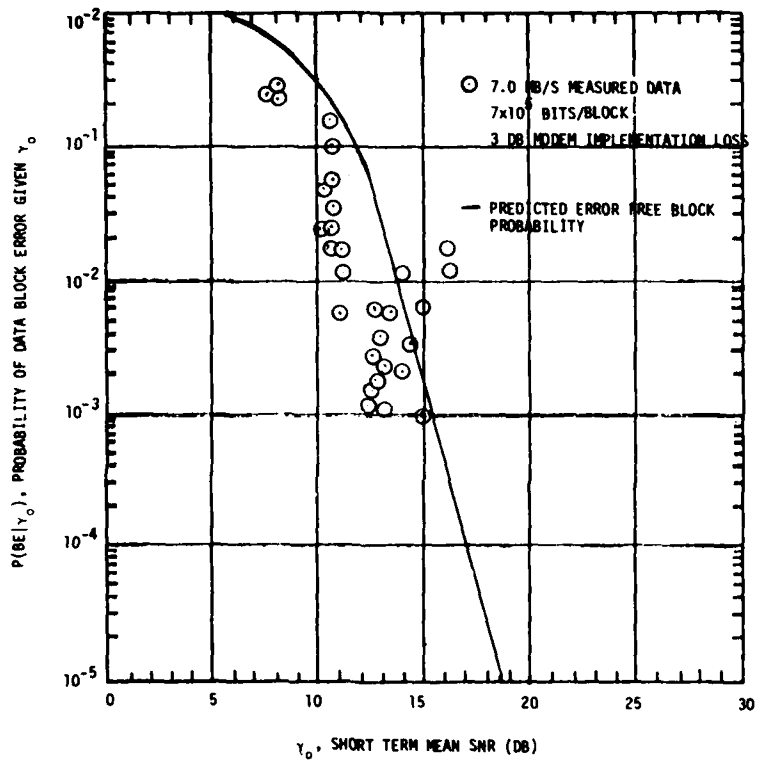


Figure 38. Troposcatter Link Block Error Probability

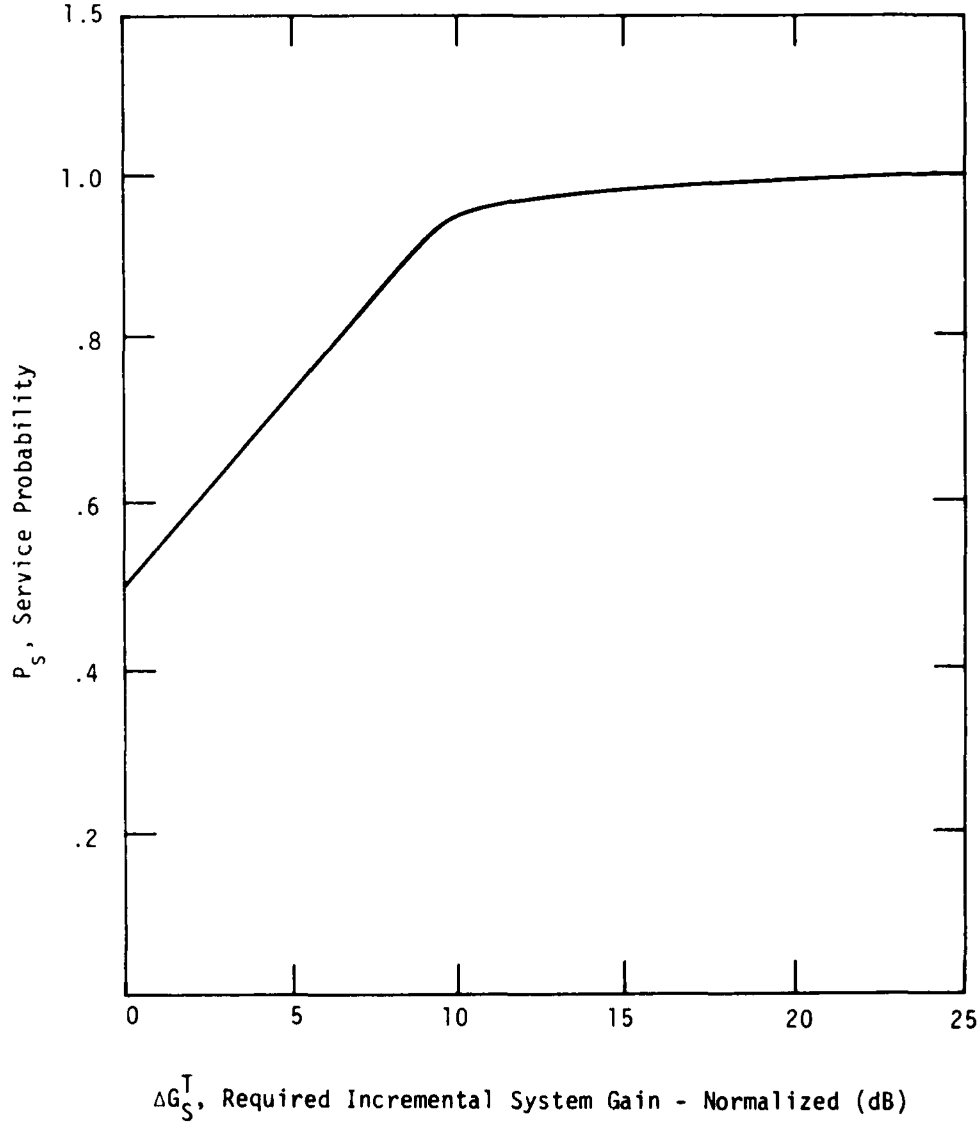


Figure 39 . Incremental System Gain as a Function of Service Probability

link, the quad diversity C-Band link design criteria listed in Table XIII, at varying service probabilities. Figure 39 reveals that the incremental system gain, ΔG_s^T, increases rapidly with increasing service probability, P_s. The apparent assymptotic behavior of ΔG_s^T which is observed as P_s increases beyond 0.95 parenthetically suggests that a small number of anomolous troposcatter links can be expected in a large network such as the DCS no matter how much care is taken during the initial link engineering phase.

As mentioned before, the design of a troposcatter link to provide the required performance at a service probability of 0.5 will result in significantly reduced system gain requirements and cost (7-10dB/$200K per link). A question then naturally develops as to whether a specific link connectivity is worth the increased expenditure of funds to provide the increased system gain (and hence, additional design confidence) or whether a design to a minimal service probability (.5 to .75) will be sufficient. To answer this, the importance of actual circuit allocations on a particular troposcatter link and the availability of alternate routing must be known, a subject which is beyond the scope of this report. However, it is known that many DCS troposcatter links serve remote areas where extensive alternate routing during periods of link outage is unavailable (e.g., Italy, Greece, Turkey). In view of this, it is probably accurate to assume that all DCS troposcatter multi-channel connectivity requirements include individual channel requirements of sufficiently high priority that a link design to a minimal service *probability will not be sufficient.* Also, the cost of even the most austere troposcatter system together with alternate routing make it prudent to insure significant link margin so that the system will perform satisfactorily when installed.

Considering the options for increasing system gain available to the system designer (e.g., increasing antenna size and power output and reducing receiver noise figure), it is readily seen that an increase of no more than 10 dB of system gain is technologically reasonable for most DCS links assuming an installation that provides a service probability of 0.5. An incremental system gain of 10 dB relative to the installed link service probability of 0.5 will move the achievable service probability to approximately 0.95 on most links. Based on this, it is recommended that the RF equipment used on all DCS digital troposcatter links be upgraded if necessary to provide a service probability of 0.95 unless specific exception is made due to ready availability of alternate routing, a lack of user priority, a sufficient quantity of accurate measured path loss data, or operational expediency.

V. TRANSMISSION SYSTEM ENGINEERING CONSIDERATIONS

The successful development of a megabit digital troposcatter transmission capability is not sufficient to guarantee its applicability to an operating communications system such as the DCS. Prior to planning for the actual implementation of digital troposcatter links, a number of system engineering issues must be addressed to insure that prototype digital troposcatter transmission hardware will be compatible with the operational constraints of the evolving DCS. These issues are summarized in Table XIV along with their impacts on the design of specific digital troposcatter components.

TABLE XIV. DIGITAL TROPOSCATTER SYSTEM ENGINEERING ISSUES AND COMPONENT IMPACTS

SYSTEM ENGINEERING ISSUE	COMPONENT IMPACT MODEM	 RF EQUIP	 ANTENNA & FEED SYSTEM
o Link Capacity	P	S	S
o Bandwidth Availability	P	P	S
o Conversion to Higher Frequencies	S	P	P
o EM Vulnerability	P	P	S
o Cost/Performance Balance	P	P	S
o Facilities Design	S	P	P
o Digital Equipment Compatability	P	N	N

LEGEND

P = Primary Impact
S = Secondary Impact
N = No Major Impact

1. LINK CAPACITY

As discussed earlier, troposcatter transmission of data rates up to 12.6 Mb/s is technologically feasible but possible only at the expense of significant system gain due to broadband transmission component losses. Fortunately, an estimate of DCS troposcatter requirements as summarized in section I indicates that approximately 86 percent of the projected DCS troposcatter link requirements can be satisfied at input data rates of 6.464 Mb/s or less and all currently projected requirements can be satisfied at 9.696 Mb/s or less. The development of broadband power amplifiers (i.e., 10 MHz, 1 dB BW) at C (4.4-5.0 GHz) and S (2.5-2.7 GHz) bands with 10 kW rated output power will allow the reliable transmission of rates greater than 9.696 Mb/s. These objectives were being addressed in the U.S. Army Efficient Reliable High Power Amplifier (ERHPA) program at S and L (755-985 MHz) Bands [22]. However, the change in lead MILDEP responsibility for DCS troposcatter to the Air Force has caused this R&D effort to be deferred pending definition of requirements. The intrinsic bandwidth limitations of L-Band high power klystron tubes are likely to limit DCS troposcatter transmission to rates of 9.696 Mb/s or less in the 755-985 MHZ frequency range The development of C-Band klystrons with sufficient bandwidth has occured under the AN/TRC-170 full scale development program.

2. BANDWIDTH AVAILABILITY

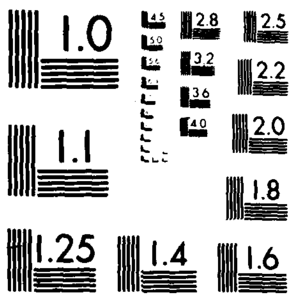
Because DCS troposcatter links presently operate in the 755-985 MHz, 1.7-2.7 GHz, and 4.4-5.0 GHz frequency bands, bandwidth allocations vary widely. Current FDM/FM bandwidth allocations are 3.5 MHz or less in these bands. Discussions with host nations have resulted in the possibility of a 7.0 MHz allocation and on an exceptional basis, a 10.5 MHz allocation for digital links. Since the majority of the projected digital troposcatter link requirements identified in section I will be implemented at 6.464 Mb/s, digital troposcatter facilities must be capable of transmitting 6.464 Mb/s plus a radio overhead composed of a 192 kb/s service channel and radio framing in no more than 7.0 MHz; also 9.696 Mb/s plus radio overhead must be transmitted in no more than 10.5 MHz. As a design objective, transmission of 9.696 Mb/s plus radio overhead in 7.0 MHz is desired. In frequency bands where 7.0 MHz allocations are presently unavailable, a 6.4 or 9.6 Mb/s throughput requirement may be satisfied by implementing a particular link in quad space-angle diversity, rather than using space-frequency diversity and acquiring multiple adjacent narrowband allocations, through a special host country agreement. This agreement could possibly be based on promised link deactivations elsewhere within the host country.

The feasibility of obtaining two contiguous narrowband allocations is not as remote as may first appear. Broadband transmitter noise resulting from klystron amplifiers which provide the high effective radiated powers typical

AD-A107 303 DEFENSE COMMUNICATIONS ENGINEERING CENTER RESTON VA F/G 17/2.1
APPLICATION OF DIGITAL TROPOSCATTER TO THE DCS.(U)
SEP 80 J L OSTERHOLZ, W J CYBROWSKI
UNCLASSIFIED DCEC-TR-10-80 NL

2 of 2

END
DATE FILMED
12 81
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

100-130 dBm) necessary for troposcatter transmission generally prohibits usage of contiguously adjacent channels and requires frequency planners to implement defacto "guard bands" between noncontiguous adjacent channels. These guard bands are designed to protect the receivers of nearby links against the 1 percent of the transmitted power which is currently permitted to radiate outside of the authorized bandwidth. If for digital transmission, limits on radiated power density (rather than total radiated power) outside the authorized bandwidth can be guaranteed, it may then be possible to use these guard bands for actual transmission and provide a measure of relief in the lower frequency bands. Additionally, significantly fewer DCS troposcatter links are expected to be retained within any one region, and thus the present congestion in the troposcatter frequency bands is also expected to be reduced.

A candidate specification format for imposing limits on out of-band transmitted spectrum density is found in FCC Docket 19311 [23] which has been adopted for DCS LOS systems. Docket 19311 specifies a maximum allowable out-of-band power spectral density in terms of a "spectrum mask" for wideband digital line-of-sight (LOS) microwave transmission systems. However, a comparable standard for digital troposcatter transmission must be developed from an analysis that specifically addresses the system sensitivities of troposcatter transmission. This area is currently under study. In the interim, DCS digital troposcatter bandwidth needs will be specified in terms of the bandwidth containing 99 percent of the transmitted power.

3. CONVERSION OF DCS TROPOSCATTER LINKS TO HIGHER FREQUENCIES

Even with the spectrally efficient implementation of digital modulation techniques, obtaining necessary bandwidth allocations is expected to be a problem in certain regions of the world. Generally speaking, the overall availability of wideband frequency allocations is seen to increase in proportion to the operating frequency. For example, increasing numbers of European television broadcasts, navigation systems, and mobile services populate or bound the 755-985 MHz band, while there is comparatively lesser congestion in the 4.4-5.0 GHz band. Thus, at first glance, it appears that the conversion of all DCS troposcatter facilities to operation in C-Band (4.4-5.0 GHz) would be desirable using, perhaps, AN/TRC-170 RF equipment currently under full scale development for TRI-TAC [24] with the MD-918 modem for spectrum efficiency. However, examination of Figure 40 graphically indicates otherwise.

Figure 40 shows the dependence of system gain (as defined previously in section IV) on operating frequency for a hypothetical smooth earth path of 200 miles (322 km) in length. Note from Figure 40 that, as the operating frequency increases, the available antenna gain (increasing with frequency as 30 log f), and tropospheric scatter path loss (which also increases but at a rate of only 20 log f) results in a larger available system gain.

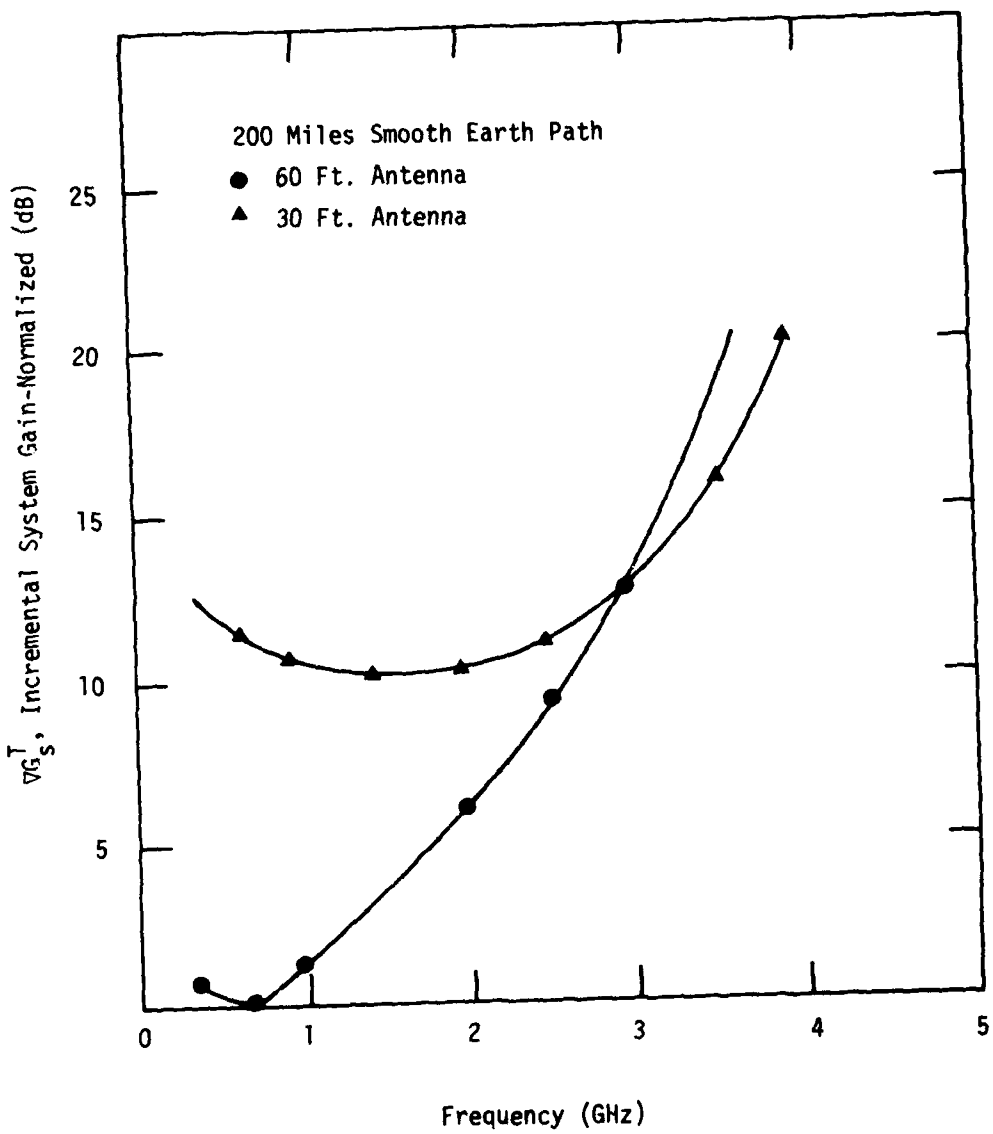


Figure 40. Required System Gain vs Frequency

Unfortunately, tropospheric scattering also causes a reduction in the coherent dimensions of the wavefront as seen by the receive antenna. The magnitude of this phenomena also increases with operating frequency and results in a decrease in system gain. This "Aperture-to-Medium Coupling Loss" [23] generally becomes significant at frequencies greater than 2.0 GHz, particularly for 30 ft (9.2 m) and larger antenna apertures. As an example, use of a 30 ft (9.2 m) antenna at 4.5 GHz on a 200 mile smooth earth link can require on the order of 7-10 dB of additional system gain to provide the same performance that can be obtained at 2.4 GHz with the same 30 foot antenna. The actual amount of additional required system gain is, of course, dependent on link geometry. Compounding the problem of achieving sufficient system gain at C-Band is an uncertainty in the prediction of the aperture-to-medium coupling loss, itself. Various methods [25,26,27] have been proposed, each claiming the support of "measured data". As seen in Figure 41, each of these methods predicts different values for aperture-to-medium coupling loss. Only one effort, however, has realistically considered aperture-to-median coupling loss on the basis of physical observations of tropospheric meterology. This method was developed under the Adaptive Antenna Control (ACC) RDT&E Program [25] and will be used for DCS troposcatter link engineering.

As implied above, the reengineering of DCS troposcatter links to frequencies above those already in use is not generally desirable and should not be initiated without first determining whether the currently used frequency bands are available. In negotiations pursuant to the World Administrative Radio Conference-1979 (WARC-79), U.S. DoD use of troposcatter frequency bands will be questioned by those nations wishing to regain use of those bands for national purposes. Figure 42 provides an approximate indication of the acceptable frequencies of operation for DCS troposcatter configurations over path lengths inclusive of DCS requirements.

For those troposcatter links which must be reengineered to higher frequencies, detailed engineering (to include path loss testing where feasible) must be accomplished prior to the commitment to install new equipment. As noted in Figure 42, the use of higher frequencies (e.g., 4.4 to 5.0 GHz) for troposcatter will, in general, be restricted to paths less than 150 miles in length where the aperture-to-medium coupling loss is less severe. It is possible, however, that this loss can be reduced somewhat by employing a multiple aperture antenna structure such as angle diversity. If aperture-to-medium coupling losses at C-Band can be reduced, utilization of tactical troposcatter RF equipment may be increased.

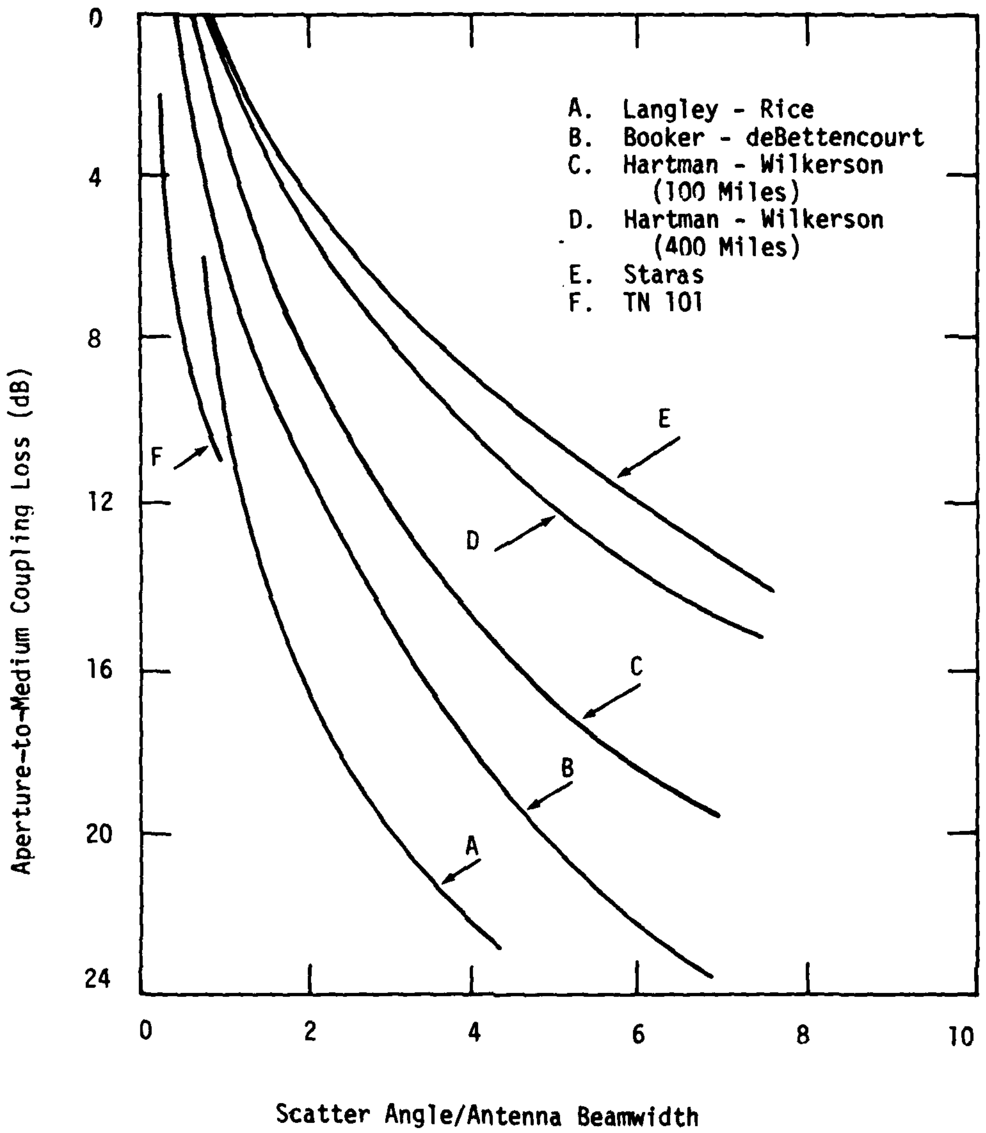


Figure 41. Aperture-to-Medium Coupling Loss vs Scatter Angle/Antenna Beamwidth (Data Taken From Hamsher)

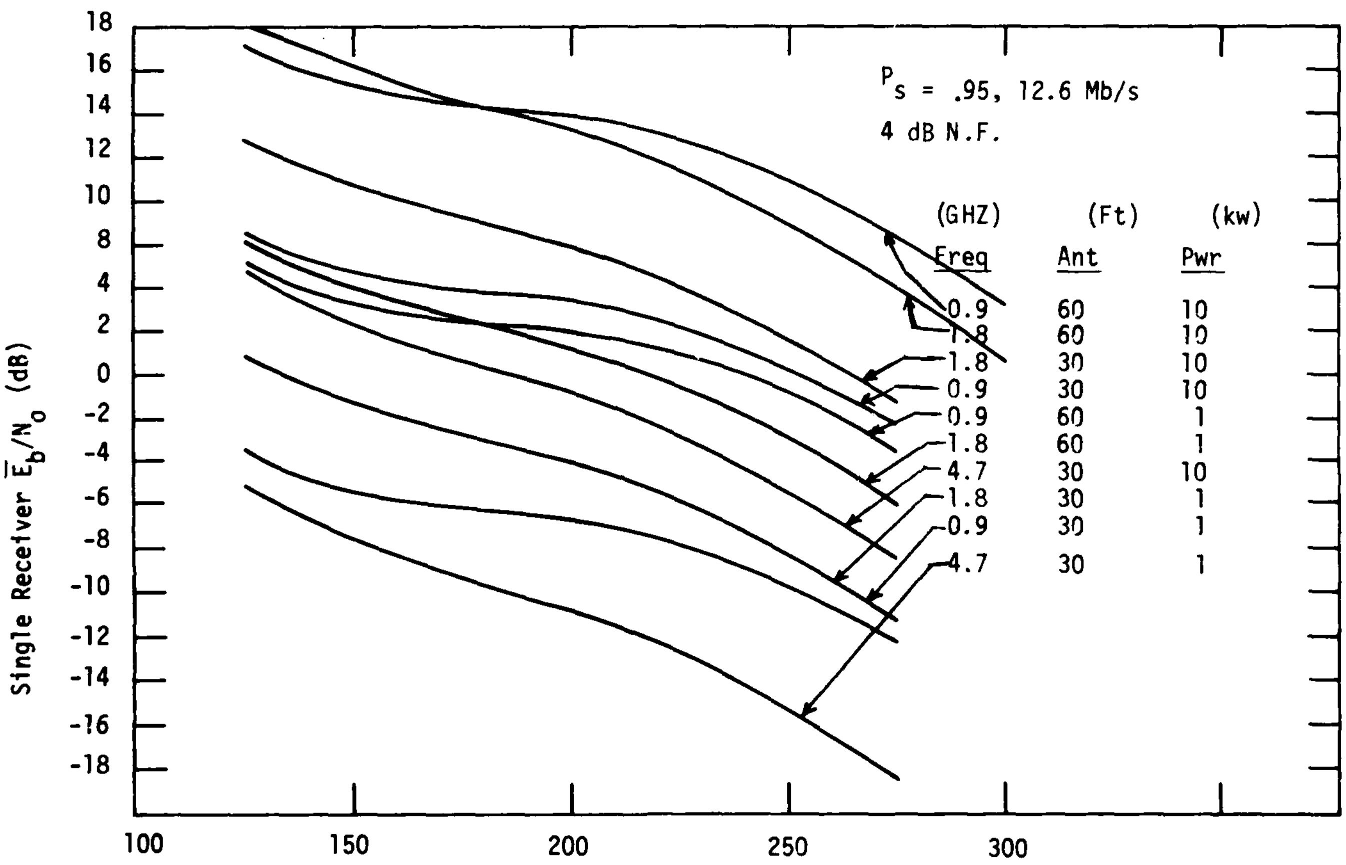


Figure 42. Relationship of Path Distance and Frequency to Loss

4. TROPOSCATTER FACILITY DESIGN/O&M REDUCTION

Current average link manning requirements, reflecting authorized rather than actual manning levels for the various DCS transmission media, have been addressed by DCEC in DCS transition planning documents. These documents indicate that troposcatter, as a transmission medium, falls half-way between comparable cross section LOS and satellite facilities in these requirements for station manning. Other data indicate that many troposcatter links have associated tech control facilities and therefore a determination of the actual per link manning is difficult. Before DCS troposcatter facilities are digitized, a comprehensive review of station manning requirements and operational procedures should be accomplished.

The thrust of this evaluation should stimulate the development of minimal manning concepts for troposcatter by reviewing the currently alleged labor intensive maintenance and operational practices used in the major analog troposcatter systems (e.g., 486L). An appropriate perspective by which to structure such a review is defined by the natural tradeoff between system MTBO and facility MTBF. MTBO by its very nature is based on a mix of component and end item redundancies. Facility MTBF is also based on redundancy but is antipodal to MTBO. That is, the overall MTBF of a facility will generally decrease in measure to any increase in required MTBO, specifically if a specific MTBO requirement is met by increasing the number of redundant end items in the facility. A decrease in facility MTBF (defined as the MTBF of all facility components in series) can require increased attention by maintenance personnel and therefore could contribute to increased maintenance cost. Nevertheless, the failure mode of digital equipments should result in changes in the preventive maintenance philosophies and practices of the MILDEP's. A 50 percent reduction in required station manning levels appears feasible and should be specified as a facilities design goal. It should be noted that a goal can only be achieved over the long term, since current new plant investment cost limitations may require the retention of much of the older analog plant for the foreseeable future.

5. DIGITAL EQUIPMENT COMPATIBILITY

The fading nature of the troposcatter channel presents certain unique problems in the design of a digital communications system, be it synchronous or asynchronous. Conventional transmission engineering approaches to the maintenance of system synchronization have generally been developed without recourse to the statistics of the fading channel. In fact, most published analyses [28, 29, 30] with only a few exceptions do not acknowledge the effects of multiplicative noise. Almost all treatments that actually make use of fading statistics are confined to discussing maintenance of transmitted symbol (i.e., baud) synchronism without recognition of the equally important area of frame, word or bit synchronization maintenance (e.g., in a Time Division Multiplex).

The salient concerns of frame synchronism or Bit Count Integrity (BCI) maintenance in a fading channel are readily seen by considering a simplified Time Division Mutiplex (TDM) design. Frame synchronism in a TDM is generally maintained by insuring a required level of correlation between a periodically transmitted bit sequence or frame pattern which is added by the transmit multiplex equipment and a locally generated replica of the transmitted sequence stored at the distant end demultiplex. Because the intervening transmission channel cannot be considered error free, correlation between the received frame pattern and the locally generated reference will not always be perfect. Since frame synchronization is generally accomplished digitally (by tracking the coincidence between bits of the received and reference sequences), it is appropriate to define the nearness to loss of synchronism by the number of noncoincidences stored in a correlation accumulator.

If the number is less than a specified threshold value, then frame synchronization is indicated. Conversely, if the threshold is exceeded, loss of synchronization is generally indicated. Certainly if there is an actual loss of synchronization or bit count integrity (BCI) in the TDM, then monitoring the magnitude of the correlation accumulator will undoubtedly detect the loss. However, if its magnitude is less than the threshold value due to transmission errors (e.g., fading), then resynchronization solely on the basis of exceeding the threshold can potentially result in a significant system unavailability penalte because the fade outage will be extended due to resynchronization time. More sophisticated TDM designs utilize up/down counters to reduce the effect of isolated instances of frame decorrelation by providing longer spans of frame correlation. While this approach certainly reduces the chance of a false declaration of loss of frame synchronism, false declarations can still occur if the capacity of the up/down counter (which should be inversely proportional to the expected channel fade rate) is not large enough to span the expected duration of frame error bursts during fading.

Thus, the design of a digital transmission system in which troposcatter will be used must explicitly address the probability that a false declaration of synchronization loss can occur. From this consideration, strategies can then be developed to reduce the overall probability of a VF channel outage due to a loss of synchronization somewhere in the digital system. That is, the probability of synchronization loss while the channel is still capable of use should be a negligible portion of the overall system outage probability. Since there are a number of "levels" or points in the digital transmission system where either symbol or bit synchronization must be maintained, and since most of the digital transmission system components are not specifically optimized for troposcatter application, the impact of timing stability on resynchronization at each of these levels should be explored and then the system component(s) should be identified that are most likely to lose synchronization due to error burst during deep fades. Figure 43, which is a Markov state diagram representing the various loss of synchronism modes that can occur at each of the synchronization levels of a hypothetical tropo system is provided as an aid. To support the following discussion of system timing stability, the results of digital troposcatter system tests conducted at Rome Air Development Center (RADC) and on the NATO ACE High system will be used.

a. Loss of Synchronization at the Digital Troposcatter Modem Level. As discussed in section II, the troposcatter channel can be considered as "elastic" in time (e.g., variable propagation path delays of 0.1 to 1 microsecond are possible). Because of this phenomenon, a rapid change of symbol timing epoch due to a short term change in the troposcatter media can occur and, at megabit transmission rates, occasionally cause a loss of BCI. The probability of loss of BCI due to variable propagation delay is denoted P in Figure 43. Figure 44, obtained during media simulator performance testing of the MD-918(GRC) modem, illustrates the rather large expected short term dynamic range of the multipath delay (or channel impulse response) for a moderately dispersive simulated troposcatter link. The simulated link described by Figure 44 had a double sided rms dispersion, or 2σ, on the order of 0.390 μsec. This figure confirms that large shifts in the symbol timing epoch can occasionally be observed and, if such shifts exceed the capability of the modem symbol tracking loop, result in BCI loss.

Even though data on the actual short term distribution of troposcatter channel dispersion are currently scarce, it is still possible to estimate empirically the effect of dispersion on link and system synchronization. Figure 45 is a plot of the Mean Time to Loss of BCI (MTLBCI) for the MD-918(GRC) digital troposcatter modem as a function of mean SNR γ_o (defined in section III) which was obtained during the digital troposcatter system tests of RADC described earlier in this section. The nominal double-sided rms multipath, 2σ, measured on the test link was on the order of 0.15 to 0.18 seconds. From Figure 45, it can immediately be seen that the MTLBCI for the MD-918(GRC) increased significantly as the SNR decreased below 4 dB. Loss of BCI due to changes in symbol timing was not observed since the MTBCI measured was such a strong function of γ_o over the nominal 1000 second length of each test. Loss of BCI due to abrupt changes in channel impulse would be expected to have caused a large scatter of data around a particular since it has been established that variations in γ_o and in the channel impulse response are very weakly correlated [5]. As shown in Figure 45, the probability of loss of BCI due to abrupt changes in propagation delay for links designed to the criteria outlined in section IV should be relatively small, and

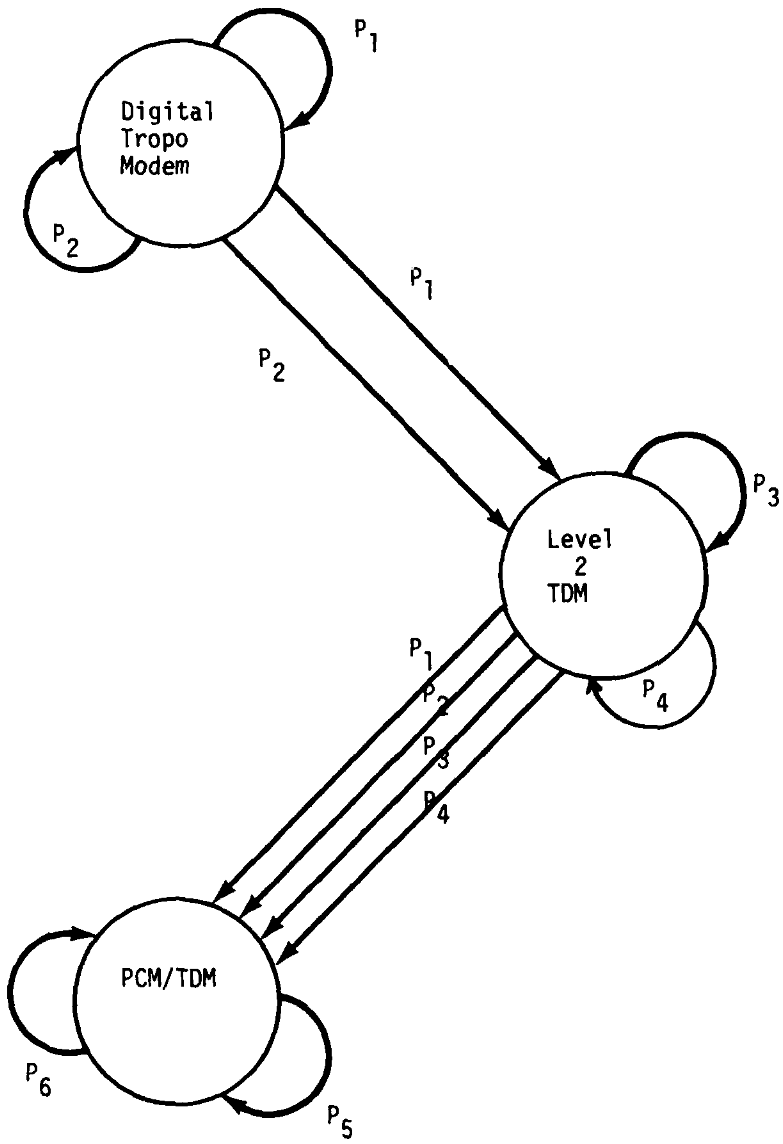
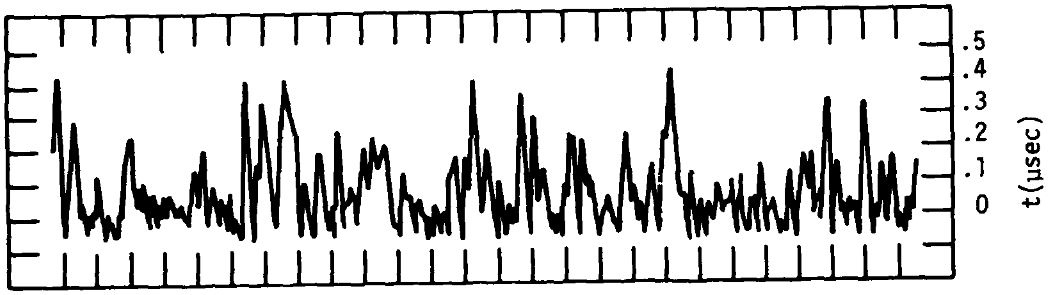


Figure 43. Markov State Representation of Synchronization Loss Hierarchy



RMS Fade Rate ∿ 5 Hz

Figure 44. Simulated Short Term Channel Dispersion

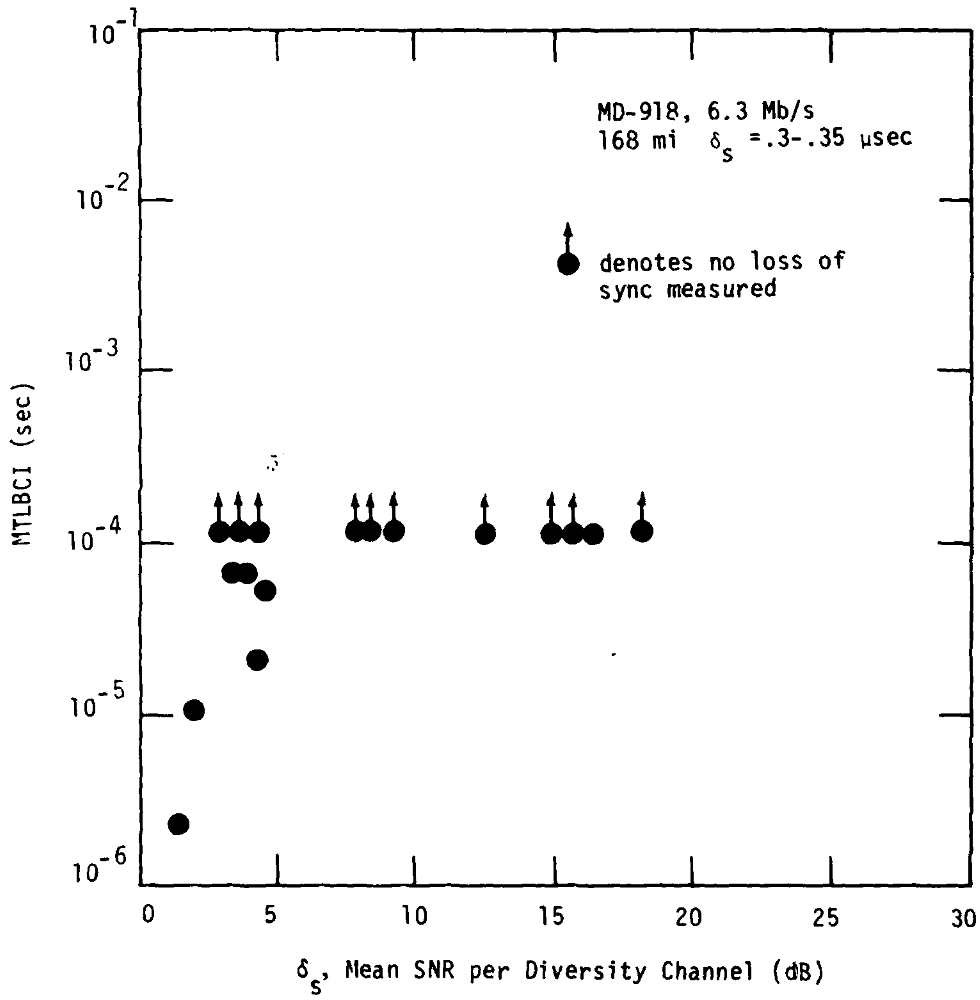


Figure 45. Mean Time Between Loss of BCI - Digital Tropo Modem

therefore loss of BCI due to media anomolies should not constitute a significant troposcatter link unavailability penalty.

Of greater potential concern is the probability that BCI will be lost within the internal TDM circuitry of the tropo modem from a falsely declared loss of frame due to fading (denoted P(2) in Figure 43). Fortunately, if the fading statistics of the propagation channel can be estimated, it is a relatively straightforward matter to design the TDM frame strategy. As an example, a TDM frame strategy which would operate effectively in the presence of troposcatter fading has been designed by DCEC and is summarized in Osterholz and Smith [20]. In reference [20], the use of transmission performance monitors to give an indication of the SNR present in the channel can be used and thereby reduces the possibility that the internal TDM (or even external, subordinate level TDM equipment) will falsely declare a loss of synchronism during a deep fade is discussed. As a corollary, this approach will permit a reduction of the frame overhead bit rate needed to achieve a given level of BCI protection. Returning to Figure 45, it is seen that the probability of a false declaration of synchronization loss is not expected to be significant for well-designed troposcatter links (i.e., links designed in accordance with the objectives stated in section IV). However, the use of transmission performance monitors to control TDM resynchronizations will also insure that a minimum probability of false frame loss occurrences in the TDM equipment will occur.

b. Loss of Synchronism in the Level 2 TDM. As can be seen in Figure 43, loss of synchronism in the Level 2 TDM (e.g., the AN/FCC-99 [30]) can stem from two major external causes: Resynchronization of the digital troposcatter modem, or resynchronization of the subordinate level TDM from fading effects similar to that described for the digital troposcatter modem internal TDM. This latter probability is denoted P_3 in Figure 43. MTLBCI data for the level 2 TDM obtained during the system tests using the MD-918(GRC) digital troposcatter modem and AN/GSC-24 TDM are shown in Figure 46. Figure 46 indicates that for the AN/GSC-24, the probability of synchronization loss in the level 2 TDM due to fading effects is expected to be extremely small if the intervening digital troposcatter links are designed with sufficiently high SNR.

It is more likely, though, that the AN/FCC-99 rather than the AN/GSC-24 will be used for DCS troposcatter digital upgrades due primarily to its higher reliability. The TDM frame strategy currently specified for the AN/FCC-99 is not as robust as that implemented in the AN/GSC-24. However, it is expected that the AN/FCC-99 design will be robust enough to make the unavailability penalty due to false resynchronization insignificant as long as DCS link design objectives are met. For digital troposcatter links where, for operational reasons, the DCS link design criteria cannot be met, a frame inhibit signal derived from the modem performance monitoring circuitry could be used to externally inhibit

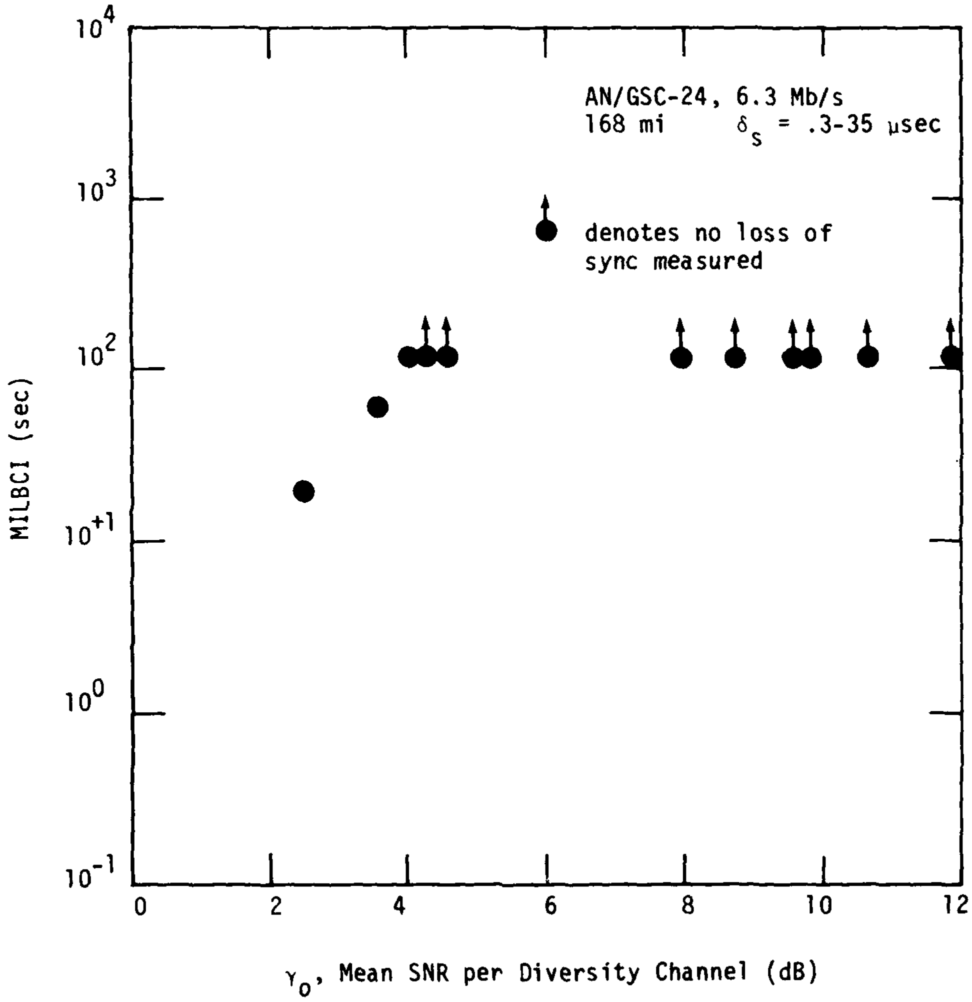


Figure 46. Mean Time Between Loss of BCI - Level 2 TDM

resynchronization of the AN/FCC-99 during deep fades. Both the MD-918/GRC( ) modem and the AN/FCC-99 equipment presently have frame inhibit signal output and input ports respectively, their electrical and functional compatibility will need to be verified before implementation.

c. Loss of Synchronization at the PCM/TDM Level. For asynchronous boundries within the system such as the initial Level 2 TDM-PCM/TDM interface, BCI will be maintained via pulse stuffing techniques. With pulse stuffing, unsynchronized PCM/TDM or other digital sources (each operating at slightly dissimilar bit rates) are combined with "stuff bits" to convert them to specific fixed rates for synchronous multiplexing within the Level 2 TDM (e.g. AN/FCC-99). Since these digital sources are unsynchronized, their bit rates will vary according to the stability of their internal timing circuits. Thus the number of stuff bits transmitted (or stuff and destuff bits if positive/negative pulse stuffing is used) will also vary. The asynchronous Level 2 TDM in its asynchronous mode must then transmit information relating the exact number of bits added (or deleted) at a particular asynchronous port to the distant end demultiplexer. Failure to do so will result in a loss of synchronism for the distant end PCM/TDM demultiplexer connected to that port.

Propagation sensed errors in decoding the number of bits stuffed or destuffed can thus cause a loss of BCI. Recognizing that real transmission channels are not error free, TDM designers protect this "stuff code" by transmitting it redundantly. In a channel where errors occur independently, the greater the degree of stuff code redundancy, the smaller the probability that an error in decoding the stuff code will be made. Thus the probability of loss of BCI due to incorrect stuff decoding (denoted P in Figure 43) is correspondingly reduced. However, for the slow fading LOS or tropo channel, it is also necessary to spread the redundant stuff control bits out in time to reduce the effect of non-independently occurring errors - the normal bit error mode observed on these channels. Failure to do this can reduce the improvement achievable with the redundant code word. DCEC TR 12-76, DCS Digital Transmission System Performance [1], sets objectives for the acceptable unavailability penalty attributable to outages caused by TDM resynchronizations.

To enhance Level 2 TDM performance on troposcatter links, the AN/FCC-99 also has the capability to operate synchronously. In this mode, the pulse stuffing process is disabled, preventing loss of BCI due to an error in stuff code detection. This mode is particularly attractive for application to troposcatter links with a low yearly median RSL and a small standard deviation about the yearly median, or on links where a high incidence of anomalous fading can be expected to cause a loss of BCI. In order to utilize the AN/FCC-99 in its synchronous mode, all digital input sources, such as PCM/TDM inputs, must be timed either by a single master timing source or, if the sources are physically separated, by a number of highly stable timing sources. The latter "quasi-synchronous" mode is termed "plesiochronous" in that many oscillators are used to accurately but independently time at least an equal number of digital sources. Loss of BCI due to source-sink timing offset between the near and distant end multiplexer will occur with a frequency defined by the stability of the independent oscillators. The achievable mean time between loss of BCI (MILBCI) can be increased significantly by the installation of buffers at the PCM/TDM level to compensate for a limited amount of input rate drift. On some DCS troposcatter links, the objectives stated in DCEC TR 12-76 for a reference digroup often will be met only by using the AN/FCC-99 in its synchronous mode and only then with appropriately sized buffers. If the augmented stuff code used on data obtained from the initial DCS digital troposcatter link implementations proves less robust than expected, use of buffers at the 1.544 Mb/s level may be required on a more frequent basis and possibly also on digroup connections which span multiple digital troposcatter hops.

Nevertheless, the equipment most likely to cause unavailability penalty (resulting in a VF channel outage) due to resynchronization is the PCM/TDM. Loss of BCI in the PCM/TDM can result from a number of essentially independent events at the PCM/TDM level as well as certain events interrelated with the proximate TDM. To elaborate, the PCM/TDM may lose BCI if the proximate TDM erroneously detects the asynchronous stuff control words associated with the particular PCM/TDM port itself. A loss of BCI in the PCM/TDM could also stem from an erroneous addition or deletion of clock pulses in the PCM/TDM timing circuitry or from a false indication of frame loss due to a deep fade. The probabilities of BCI loss due to the latter two phenomena are denoted P_r and P_ℓ respectively in Figure 43. P_r should be negligible assuming a sound installation, while P_ℓ depends on the error environment of the intervening link(s). Analysis and experimental data have shown that if the link design criteria specified in section IV are met, P_s should not be problematic since the AN/FCC-99 stuff code performance is specified as equivalent to a 9 bit stuff code. For links where the link design criteria are not met, the incremental unavailability experienced should still be tolerable as long as the link system gain deficiency is less than 3 dB. Beyond this point, synchronous operation of the AN/FCC-99 will be required.

On the other hand, P_ℓ, for the PCM/TDM equipment specified for use in the DCS (e.g., the AN/FCC-98 [31]), may not be negligible. The D2 compatible frame specified in the AN/FCC-98 is based on a "stolen bit" principle where every 193rd data bit is a PCM/TDM frame bit, resulting in an aggregate PCM/TDM frame rate of 8 kb/s. While the relatively low anticipated frame bit density of the AN/FCC-98 (relative to that expected in the AN/FCC-99) does not in itself imply a lack of robustness, the combination of low frame density and a weak framing algorithm (not optimized for fading channel application) will make the AN/FCC-98 the weakest link in the system from a synchronization viewpoint.

Figure 47 presents MTLBCI data taken on a DCS prototype PCM/TDM, the TD-968. Figure 47 includes losses of BCI due to stuff word decoding error in the Level 2 TDM as well as loss of BCI due to resynchronization in the TD-968 itself. It should be mentioned that the frame algorithm implemented in the TD-968 during these tests was not the normal D2 algorithm but rather an algorithm enhanced for degraded channel operation [32]. Therefore, Figure 47 can be interpreted as an optimistic bound on expected PCM/TDM performance that probably reflects more instances of synchronization loss due to stuff code error (P5) than false loss of synchronization due to fading (P1). If the actual AN/FCC-98 frame algorithm is not augmented beyond that implemented in current D2 PCM/TDM designs, control of the resynchronization monitor information derived from intervening links will be necessary.

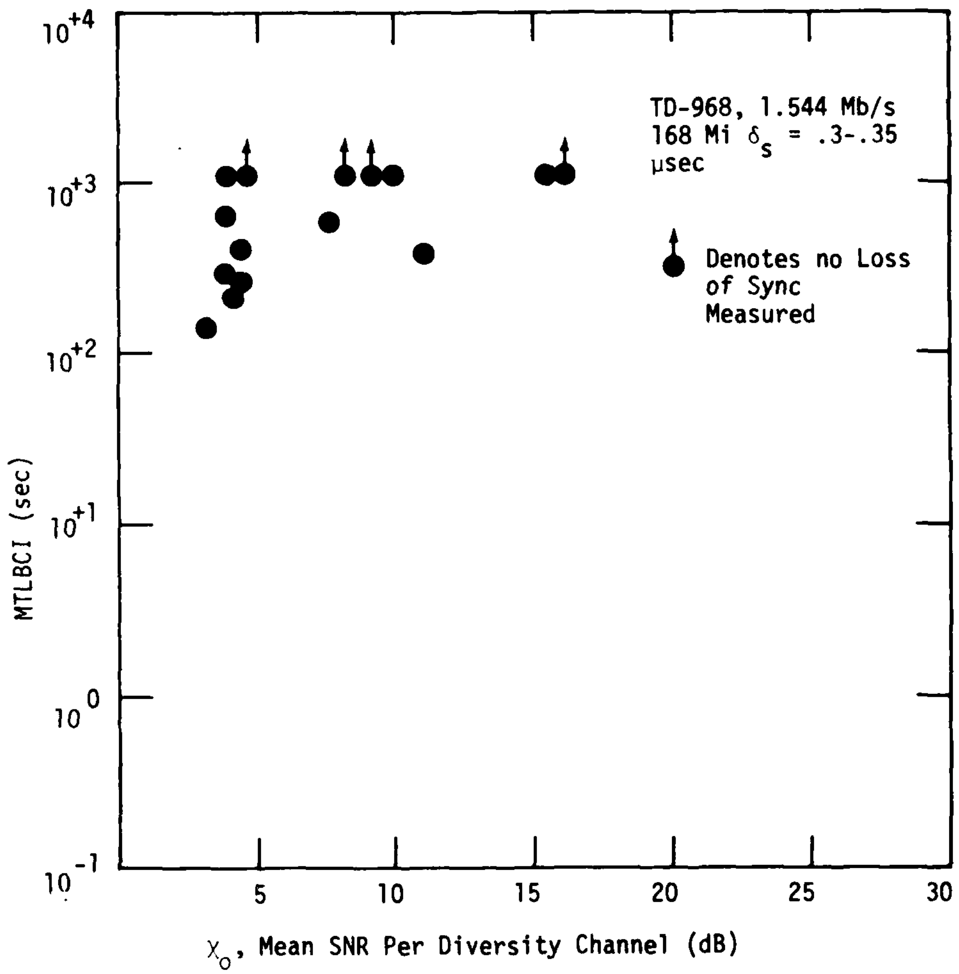


Figure 47. Mean Time Between Loss of BCI - PCM/TDM

REFERENCES

[1] DCEC TR 12-76, "DCS Digital Transmission System Performance," Nov 76.

[2] Computer Sciences Corp., "Technical Visits Program Tabulation of TVP Parameters for Tested and Untested DCS Links", 31 Jan 72.

[3] P. A. Bello, "A Troposcatter Channel Model", Transactions of IEEE Group on Communications Tech., April 1969, pp. 130-137.

[4] P. F. Panter, Communications Systems Design, McGraw-Hill, New York, 1972.

[5] National Bureau of Standards Tech Note 101, "Transmission Loss Predictions for Tropospheric Communications Systems," P. L. Rice, et al, Vols. 1 and 2, May 1965.

[6] CCIR Report 244-2, "Troposcatter Path Loss," New Delhi, 1970.

[7] Signatron Inc., RADC-TR-73-268, "Adaptive Data Transmission Study," August 1973.

[8] E. D. Sunde, "Digital Troposcatter Transmission and Modulation Theory", BSTJ 43, pp 143-214, Jan 1964 (Part I).

[9] David J. Kennedy, "A Comparison of Measured and Calculated Frequency Correlation Functions Over 4.6 and 7.6 GHz Troposcatter Paths", IEEE Transactions on Communications, April 1972, pp. 173-178.

[10] M. Schwartz, W. Bennett, S. Stein, Communications Systems and Techniques, McGraw-Hill, New York, 1966, pp. 416-489.

[11] Mitre Corp. MTP-170, "Multipath Measurements Over Troposcatter Path," A. Sherwood, L. Suyemoto, April 1976.

[12] G. L. Turin, "Communications Through Noise, Random-Multipath Channels", IRE National Convention Record Part 4, pp. 154-166, March 1956.

[13] Signatron Inc., RADC-TR-70-175, "Troposcatter Multimode FSK/PSK Modem", Sept. 1970.

[14] G.T.E. Sylvania, Inc., ECOM-0040-F, "Megabit Digital Troposcatter Subsystem (MDTS) Research and Development Technical Report", July 1976.

[15] Raytheon Co., RADC-TR-79-250, "Digital Transmission System," October 1979.

[16] M.M. Goutman, "Intersymbol Interference as a Natual Code", IEEE Transactions on Communications, VolCom-20, Nov-Oct 76, pp. 1033-1038.

[17] R. C. Fitting, H. Weber, "Sideband Diversity Modem for Digital Transmission", Proceedings of the EASCON '74, pp. 430-433.

[18] Raytheon Company, Contract No. F30602-76-C-0217, "ECCM Test Final Report," (U) September 1978 (S).

[19] Signatron Inc., Report No. SIG-79-1056, "ECM Vulnerability Test Report," (U) P. Monsen, J. Eschle, November 1978 (S).

[20] J. L. Osterholz and D. R. Smith, "The Effects of Digital Tropo Error Statistics on Asynchronous Digital System Design," Preceedings of the NTC-74, pp. 28-25 to 28-31.

[21] U.S. Air Force Systems Command-ESD, ESD-TR-CC-638, "Final Test Report European Mediterranean Tropospheric Scatter Communications System - Phase IV", Feb 1967.

[22] U.S. Army Electronics Command, "Efficient Reliable High Power Amplifier (ERHPA) - Statement of Work", Aug 1976.

[23] Federal Communications Commission Docket 19311 (Emission Standards for Digital Microwave Transmission), Sept 74.

[24] Raytheon Inc., "AN/TRC-170 Preliminary Design Review", Jan 77.

[25] H. Staras, "Antenna to Medium Coupling Loss", IRE Transaction on Antennas and Propagation, Vol A, p 5, pp 228-231, Apr 57.

[26] D. T. Gjessing and K. S. McCormick, "On the Prediction of the Characteristic Parameters of Long Distance Tropospheric Communication Links", IEEE Transmission on Communications, Vol 22, p. 1325, Sept 74.

[27] DAABO 7-76-C-8085, "Interim Report - Adaptive Antenna Control," P. Monsen, et al, December 1976.

[28] Williard, M. W., "PCM Telemetry Synchronization", Proceedings of the National Telemetry Conference, Chicago, Illinois, May 1961.

[29] Sylvania Elect. Sys. Tech Report, "Block Error Probabilities for Binary Signalling Over a Slowly Fading Channel", A. H. Levesque, W. M. Cowan and B. B. Barrow, 15 Oct 68.

[30] Hdqs. USACEEIA, CCC-74048, "Specification for Multiplexer/ Demultiplexer TD-1193( )/F," 1 March 1976.

[31] Hdqs. USACEEIA, CCC-74047, "Specification for Multiplexer/ Demultiplexer AN/FCC-98( )(P)/F," 20 August 1975.

[32] U.S. Army Electronics Command, EL-CP0047-001A, "Specification for TD-968 PCM Multiplexer," April 1969.

APPENDIX A
QUALITY ASSURANCE TEST METHODS FOR DCS DIGITAL TROPOSCATTER LINKS

I. INTRODUCTION

This appendix addresses methods for the performance assessment of DCS troposcatter links which have been installed to meet the link performance requirements specified in this report. Performance assessment is necessary for initial link and system acceptance testing and for periodic quality assurance (QA) testing. Some of the characteristics of the overall transmission system, such as the specified VF channel characteristics, are relatively straightforward to test and are not discussed here. However, the basic link performance requirements such as fade outage probability and availability are probabalistic in nature and thus their test verification is not as straightforward. This appendix presents a recommended testing philosophy for DCS digital troposcatter links to verify that these probabalistic link design requirements will be met with a high likelihood. This appendix should not be considered as an exhaustive treatment of all necessary digital tropo link testing requirements but rather as a basis for updating existing DCS circulars such as DCAC 310-70-57.

Since a single transmission link represents only a small portion of an overall user circuit, its performance must be extremely good in order that the combined performance of all links provides acceptable quality for the overall circuit. Thus, the requirements for probability of fade outage and mean-time-between-equipment-outage, when applied to an individual link, have specified values such that their verification would require a prohibitively expensive test. As an example, the mean-time-between-equipment-outages for a typical unattended LOS repeater is approximately 55,000 hours or 6-1/3 years. Clearly then, this type of parameter is not suitable for direct measurement. Thus, acceptance testing and quality assurance testing of DCS links should be aimed at verifying intermediate level characteristics of the installed links which are related to the above system-level requirements in a known way.

Examination of the various tests which provide information on the acceptability of a digital transmission link suggests a natural division into the two categories shown in Figure A1. These two categories, Verification of Link Installation and Verification of Probabilistic Link Performance, require distinctly different test approaches. The Verification of Link Installation requires such tests as receiver noise figure measurement, transmitter power output measurement, redundant component switching, and other tests which do not require extensive statistical interpetation. The Verification of

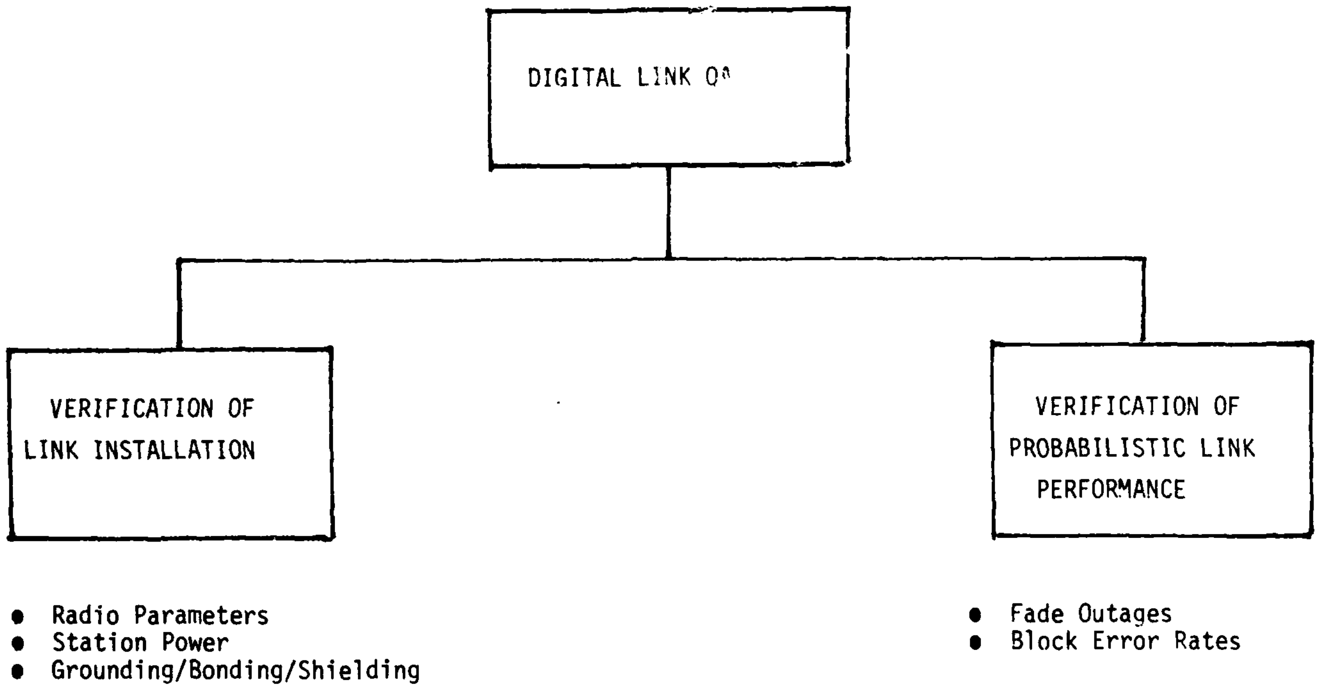


Figure A1. Digital Link Quality Assurance (QA)

Probabalistic Link Performance, on the other hand, necessitates testing with a subsequent statistical interpetation to determine whether the voice and data performance criteria will be met. Obviously, due to the relatively low expected probability of occurrence of these criteria, an absolute verification of link suitability will generally take an extremely long time. On the other hand, those tests inclusive of Verification of Link Status are mostly deterministic and are not envisioned as long term measurements. Furthermore, with the exception of digital modem testing, these link installation tests are adequately described in existing analog link test procedures. Therefore, this appendix concentrates on developing those concepts necessary to verify the probabalistic link performance of DCS digital troposcatter links since this area is not presently covered in other documents.

II. VERIFICATION OF PROBABALISTIC LINK PERFORMANCE

Because of the extreme variability of troposcatter propagation over an operating year and the rather small expected probability of fade outage, it is extremely difficult to verify the performance of a digital troposcatter link solely on the basis of a short term measurement. This observation is not new; analog troposcatter system designers faced the very same difficulties in assuring that their analog links met DCS idle channel noise specifications. Ideally, the testing of a link or collection of links over an entire operating year would provide soundly convincing evidence as to the long term acceptability or unacceptability of a transmission system. Unfortunately, it is normally impossible to allocate the entire first service year for testing. Pressures for immediate use of the system will usually limit the initial testing period to 30 days or, in some cases, as little as 5 days. A 30 day test of a troposcatter link or set of links will not, in itself, provide absolute assurance of continuing acceptability since even year to year variations in troposcatter link performance are possible. However, given the 30 day period which can realistically be made available for quality assurance (QA) testing of a multilink troposcatter system, specific tests must be developed which will maximize the accepting agency's confidence in the long term acceptability of the system.

As a background observation, note that for most true troposcatter links, daily variations will account for almost all (save about 5 to 10 dB) of the total variations that can be expected on the link over the year. This 5 to 10 dB of additional seasonably based path loss (see NBS TN 101 Vol 2) will generally be confined to a 3 month period during the winter and will be further concentrated in the afternoon quarter of each winter day. Thus, a 30 day testing period per link will then certainly provide a reasonable indication that the link can or cannot be expected to operate satisfactorily for at least 90 percent of the year.

Unfortunately, assurance that the link will provide the required overall outage probability (e.g., 7.5x10-4) cannot be obtained directly from the 30 day test. However, the vast majority of all DCS troposcatter links that will eventually be digitized have been operating as analog links for anywhere from 5 to 20 years and therefore a significant data base should exist on received signal level (RSL) variations (technical evaluation program reports) which should be accurate to the required percentile. What does not exist is similar data on multipath delay variability. Fortunately, based on available data it is possible to estimate the maximum expected multipath delay for most links and to engineer the digital troposcatter link accordingly. The observed path loss variations as measured over the analog service life of these links can be combined with predictions of the maximum expected multipath delay to estimate the performance of the link or system out to the required outage probability. Therefore, assuming reliable analog link performance data (e.g., Technical Evaluation Program Visitations) and a full 30 day test period, it is felt that the acceptability of a single digital troposcatter link or a small group of links can be assessed with reasonable confidence.

Returning to the original question of suitable QA testing methods, it remains to be determined just what quantitative procedures should be specified. It should be understood that the basic denominator of DCS digital transmission system performance is the probability of fade outage and not the more coarse indicators such as average bit error rate. As a result, probabilistic testing methods must be established which will assess the overall fade outage probability. The digital troposcatter performance model developed in section IV of this report does provide a method to predict the probability of fade outage as a function of short term mean SNR. Based on this method and the predicted long term distribution of mean SNR (or mean RSL for a specific radio), a predicted long term outage distribution (encompasing outage durations of 0.2 sec and greater) can be generated. This outage distribution, shown for a hypothetical link in Figure A2, can be used as a link accept/reject criterion. Depending on the time of the year in which the link acceptance test is conducted, measured data points should fall on or below the calculated distribution. Sufficient valid data points falling above the calculated curve could be cause for link reengineering by the installation activity and subsequent retesting. Another way of representing the data described above permits further verification that the installed digital troposcatter system is operating correctly. This representation, typified in Figure A3, characterizes the short term performance of the link (i.e., fade outage probability vs mean RSL) and can be compared to a predicted curve. While this analysis has no direct statistical significance, it nevertheless will provide added assurance that the modem is operating properly and is able to satisfactorily mitigate troposcatter induced propagation degradations.

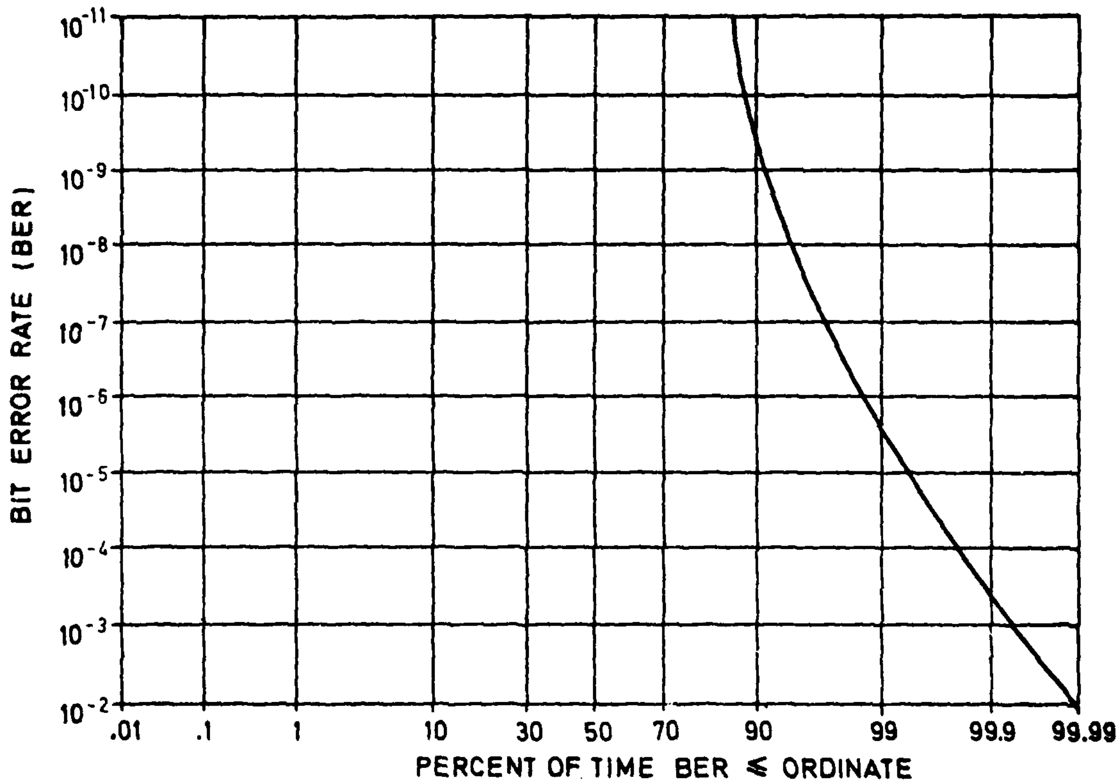


Figure A2. Hypothetical Fade Outage Distribution

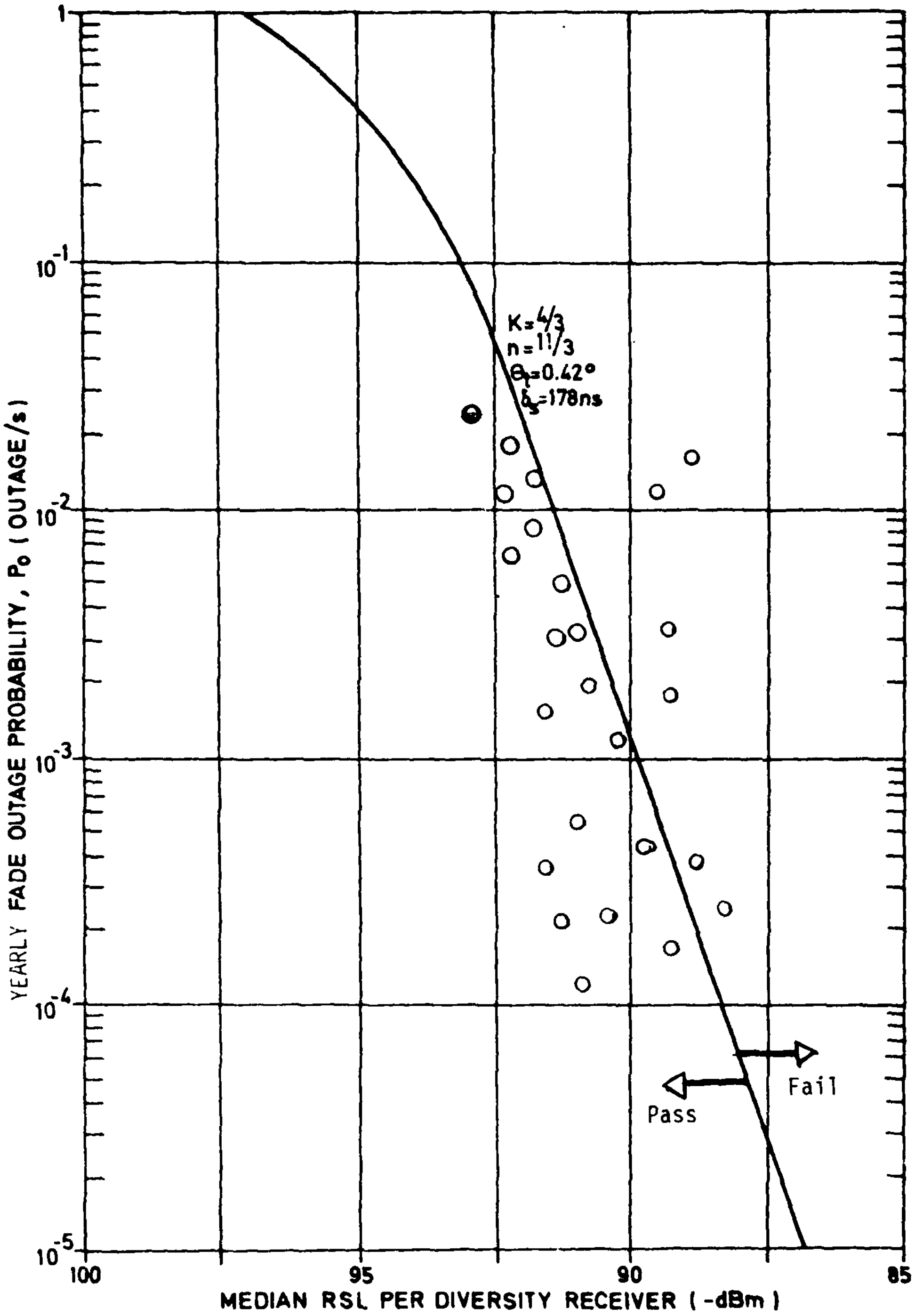


Figure A3. Hypothetical Link Pass/Fail Criteria

APPENDIX B
PERFORMANCE SPECIFICATION FOR
DCS DIGITAL TROPOSCATTER MODEM MD-( )

(DRAFT)

TABLE OF CONTENTS

PERFORMANCE SPECIFICATION FOR
DIGITAL TROPOSCATTER MODEM, MD-( )

1. SCOPE

1.1 General. This specification provides performance requirements for a digital troposcatter modem. The modem shall be capable of configuration into dual and quadruple terminal configurations when used with the troposcatter radio sets described herein.

2. APPLICABLE DOCUMENTS

2.1 Government Documents. The following documents of the issue in effect on the date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be the superseding requirement.

SPECIFICATIONS
Military

MIL-E-4158	Electronic Equipment Ground, General Requirements for
MIL-F-14072	Finishes for Ground Signal Equipment

STANDARDS
Military

MIL-STD-130	Identification Marking of US Military Property
MIL-STD-188-100	Common Long Haul and Tactical Communications System Technical Standards
MIL-STD-189	Racks, Electrical Equipment, 19-inch and Associated Panels
MIL-STD-454	Standard General Requirements for Electronic Equipment
MIL-STD-461	Electromagnetic Interference Characteristics Requirements for Equipment
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement of
MIL-STD-463	Definitions and System of Units, Electromagnetic Interference Technology

MIL-STD-471	Maintainability Verification/ Demonstration/Evaluation
MIL-STD-781	Reliability Tests: Exponential Distribution
MIL-STD-810	Environmental Test Methods
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment, and Facilities

OTHER PUBLICATIONS

TRI-TAC

TT-A3-9008-0024	Trunk Encryption Device, Interface Specification, dated 22 November 1974 for the TSEC/KG-81

USACEEIA

CCC-74047	Specification for Multiplexer/ Demultiplexer, TD-1192( )(P)/F
CCC-74048	Specification for Multiplexer/ Demultiplexer, TD-1193( )/F

RADC

CP618100C	Multiplexer Set AN/GSC-24 (V) dated 17 March 1975

Manuals (TMS) for

AN/GRC-143

AN/TRC-170 (AN/GRC-197 RADIO)

AN/FRC-39A

AN/FRC-56

AN/FRC-96

AN/FRC-97

REL 2600 SERIES
REL 2900 SERIES

(Copies of specifications, standards, drawings, and publications required by suppliers in connection with specified procurement functions should be obtained from the procuring activity or as directed by the contracting officer).

3. REQUIREMENTS

3.1 Definitions

3.1.1 Modem. The modem shall include all modulation and demodulation functions, diversity combiner functions, power supplies, fault sensing and alarm circuits, internal time division multiplex (TDM) functions, performance monitoring and display functions necessary to convert a dual or quad diversity heterodyne troposcatter radio receiver and associated transmitter to digital operation.

3.1.2 Mission Bit Stream. The mission bit stream (MBS) is that digital signal carrying subscriber message traffic.

3.1.3 Service Channel Bit Stream. The service channel bit stream (SCBS) is that digital signal carrying the required order wire and alarm functions.

3.1.4 IF Interface. The IF interface is that point where the tropo radio feedline(s) are connected to the modem at a nominal frequency of 70 MHz. All necessary IF components such as filters, attenuators and amplifiers shall be included on the modem side of the IF interface.

3.1.5 Aggregate TDM Rate. The aggregate TDM rate is defined as the composite bit rate determined with one or two MBS, one SCBS and TDM overhead.

3.1.6 Multipath Profile. The simulated multipath profile is a representation of the time dispersive troposcatter channel and is defined as the ensemble of sampled values of the delay power spectrum at intervals of 0.67 sec. The multipath profiles with which the requirements of this specification must be met are defined in Table B-I.

3.1.7 Mean E_b/N_o. Mean E_b/N_o is defined as the ratio of the mean received power measured in a bit rate bandwidth to the effective noise power (including receiver noise factor) measured in a 1 Hz bandwidth, expressed logarithmically. The mean Eb/No is 1.6 dB larger than the median Eb/No.

3.2 Performance Characteristics

The modem shall time division multiplex the one or two MBS and the SCBS, and provide two modulated 70 MHz IF carriers. The modem shall also accept up to four fading, modulated 70 MHz IF signals from the troposcatter radio receivers, and combine, demodulate and demultiplex the signals into one or two output MBS and an output SCBS.

TABLE B-I. MULTIPATH PROFILES

Attenuator Tap No.	P1	P2	P3	P4
	ATTENUATOR TAP SETTINGS IN dB			
1	0	0	2	0
2	*	8	1	0
3	*	19	4	1
4	*	28	8	2
5	*	*	13	4
6	*	*	17	6
7	*	*	23	9
8	*	*	26	11
9	*	*	*	14
10	*	*	*	17
11	*	*	*	20
12	*	*	*	23
13	*	*	*	*
14	*	*	*	*
15	*	*	*	*
16	*	*	*	*

*60 dB Attenuator Tap Setting. Settings for the Signatron Model S-139C Troposcatter channel simulator with 67 nsec tap spacings.

The MBS inputs/outputs shall operate with any cable length (3.5.4) up to and including 100 feet. The SCBS shall operate with any cable length (3.5.4) up to and including 750 feet.

3.2.1 Modem Characteristics

3.2.1.1 Input Power. The modem shall operate and maintain specified performance when connected to either one of the following sources of primary power.

a. An alternating current (ac) power source which will conform to MIL-E-4158, Table II, Condition I, and will have the following nominal steady-state ratings:

(1) Input voltage - 117/230 volts ac + 10 percent, single phase.
(2) Input frequency - 47 to 420 Hz.

b. A direct current (dc) power source having any output voltage from 44 to 56 volts, with any variation therein, negative (positive ground) with ripple and noise not to exceed 100 millivolts peak-to-peak.

3.2.1.1.1 Power Supply Protection. The modem shall meet all the requirements (ac and dc) of MIL-E-4158, Tables II, III, and IV, except that in Condition II, recovery time shall be 100 milliseconds (maximum). All major functions shall be protected against overload separately to prevent one function from affecting others. Removal or failure of a power supply shall cause no interruption or degradation of service provided by the modem. In addition, the modem shall not be damaged or sustain a service outage in excess of 100 milliseconds as a result of the application of a 1000 volt potential of either polarity for a period of 1.0 microsecond, applied at a 50 volt/nanosecond rate of rise to all input power interfaces and ground. Human intervention shall not be required to return the modem to service after the application of the specific transient.

3.2.1.2 Emission Parameters. The modem shall operate at the bit rates and bandwidths specified in Table B-II of this specification. Changes in bit rates and transmitted bandwidths shall be accomplished by module or component exchange in 8 hours or less. The use of pretuned or prealigned assemblies or components is permissible. The modem shall satisfy the emission requirements stated in paragraph 3.2.2.1 of this specification for the data rate and transmitted bandwidth combinations specified in Table B-II.

3.2.1.3 Modem Interface Requirements

3.2.1.3.1 General. The modem shall provide and accept two synchronous mission bit streams (MBS) with associated timing as well as provide and accept a single mission bit stream with associated timing at the rates specified herein. In addition, the modem shall provide and accept a 192 kb/s SCBS with associated timing which shall be synchronously time division multiplexed with the MBS(s) at the selected rate. The recovered data shall be demultiplexed after diversity combining and demodulation and provided to the appropriate output ports. The modem shall interface, without performance degradation, with the following digital equipments and shall not cause performance degradation to these equipments:

a. KG-81, TT-A3-9008-0024.
b. AN/FCC-99( )(P)/F (CCC-74048).
c. 192 kb/s Service Channel Multiplexer, AN/FCC-98 ( )(P)/F (CCC-74047).
d. AN/GSC-24(V), CP618100C.

Additionally, the modem shall interface with the following troposcatter radio equipment and shall not cause performance degradation to these equipments.

e. 2 ea., AN/GRC-143 (Quad Diversity Terminal Configuration).
f. AN/TRC-170 (V(I), V(II) and V(III)).

g. AN/FRC-39A
h. REL 2600
i. REL 2900
j. AN/TRC-132A
k. AN/FRC-56, AN/FRC-96 and AN/FRC-97.

3.2.1.3.1.1 Diversity Operation. As illustrated in Figure B-1, the modem shall provide all interface and combining functions necessary to operate the troposcatter radios listed in 3.2.1.3.1 in dual and quadruple diversity digital operation.

3.2.1.3.1.1 Transmit Modem Level. The modem shall provide two separate modulated 70 MHz IF outputs at a level which is adjustable from -4 dBm to +16 dBm in 1 dB steps. The source impedance shall be 50 ohms plus or minus 10 percent, unbalanced, measured over the modem IF bandwidth of 70 MHz plus or minus 10 MHz.

3.2.1.3.1.1.2 Receive Modem Levels. The modem shall accept 1, 2, 3, or 4 separate diversity modulated 70 MHz IF inputs from the troposcatter radios listed in 3.2.1.3.1 above. The modem shall meet the performance stated herein with a range of mean IF input signal levels of from -10 dBm to -75 dBm, inclusive.

3.2.1.3.1.1.3 Receive IF Attenuator. The modem shall provide adjustable attenuation for each diversity IF input. The attenuation shall be adjustable over a 20 dB range in no more than 5 dB steps.

TABLE B-II. TRANSMITTED BANDWIDTHS

Total MBS Rate	Bandwidth For Performance Level I*	Bandwidth For Performance Level II*
3.232 Mb/s	3.5 MHz	N/A
6.464 Mb/s	7.0 MHz	N/A
9.696 Mb/s	10.5 MHz	7.0 MHz
12.928 MB/s	14.0 MHz	10.5 MHz

* Performance Level as defined in 3.2.3.1.

3.2.1.3.1.2 MBS Interface Requirements. When the MBS of the modem (using two modems back-to-back with a mean E_b/N_o corresponding to a BER of 3 parts in 10(9)) is interconnected with the digital equipment described in 3.2.1.3.1, a through d, the BER at the output of the digital equipment shall not be increased from that measured when the modem is configured as stated above (back-to-back). The above requirement shall be met for all MBS rates (Table B-III) and for single and parallel inputs/outputs.

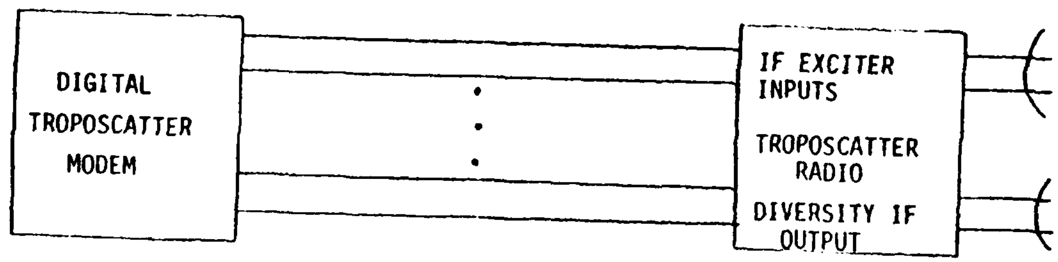


Figure B-1. Modem/Radio Interface

3.2.1.3.1.3 <u>SCBS Interface Requirements.</u> When the SCBS of the modem is interconnected to an FCC-98, the BER at the 50 kb/s data channel on output of the FCC-98 shall not be increased from that measured when the modem is configured as stated in 3.2.1.3.1.

3.2.1.3.2 <u>Data and Clock Input/Output Signals.</u> The modem shall provide and accept the data and clock input/output signals stated below and illustrated in Figures B-2a and B-2b.

a. Two MBS inputs with associated timing.
b. Two MBS outputs with associated timing.
c. One SCBS input with associated timing.
d. One SCBS output with associated timing.
e. Two MBS transmit clock outputs, phase locked to the radio transmit clock.
f. One SCBS transmit clock output, phase locked to the radio transmit clock.
g. One external clock input at the MBS rate (Table B-III) of the radio internal multiplexers.
h. One recovered receive timing output at the MBS rate (Table B-III) of the modem internal TDM function.

3.2.1.3.3 <u>Digital Input/Output Signal Characteristics.</u> The following input/output signal characteristics shall apply to all data and timing inputs and outputs of the modem. The modem shall accept serial non-return-to-zero (NRZ) polar square wave data with associated polar square wave (equal positive and negative duration) timing at the mission and service channel inputs as shown in Figure B-3. The SCBS input will be synchronous with the modem transmit clock. The modem shall provide NRZ data and timing at the mission and service channel outputs. The modem shall accept polar square wave timing at the MBS rate (Table B-III) as the external clock input. The modem shall provide polar square wave MBS and SCBS timing outputs phase locked to the modem transmit clock at the MBS and SCBS bit rates, respectively.

3.2.1.3.3.1 <u>Buffering.</u> Buffering shall be included within the modem to interface with each incoming mission bit stream. Sufficient buffer capacity shall be provided so that when the MBS source timing rate differs from the internal modem timing rate by as much as plus or minus 2 parts in x 10(6), the mean time to loss of bit count integrity shall be at least 24 hours for each MBS. These buffers shall be arranged to automatically reset in the event of overflow or underflow.

3.2.1.3.3.2 Output Characteristics

3.2.1.3.3.2.1 <u>Impedance.</u> The output impedance for NRZ data and timing shall be 78 ohms plus or minus 10 percent (balanced). The capacitive shunt shall be less than 15 picofarads to ground.

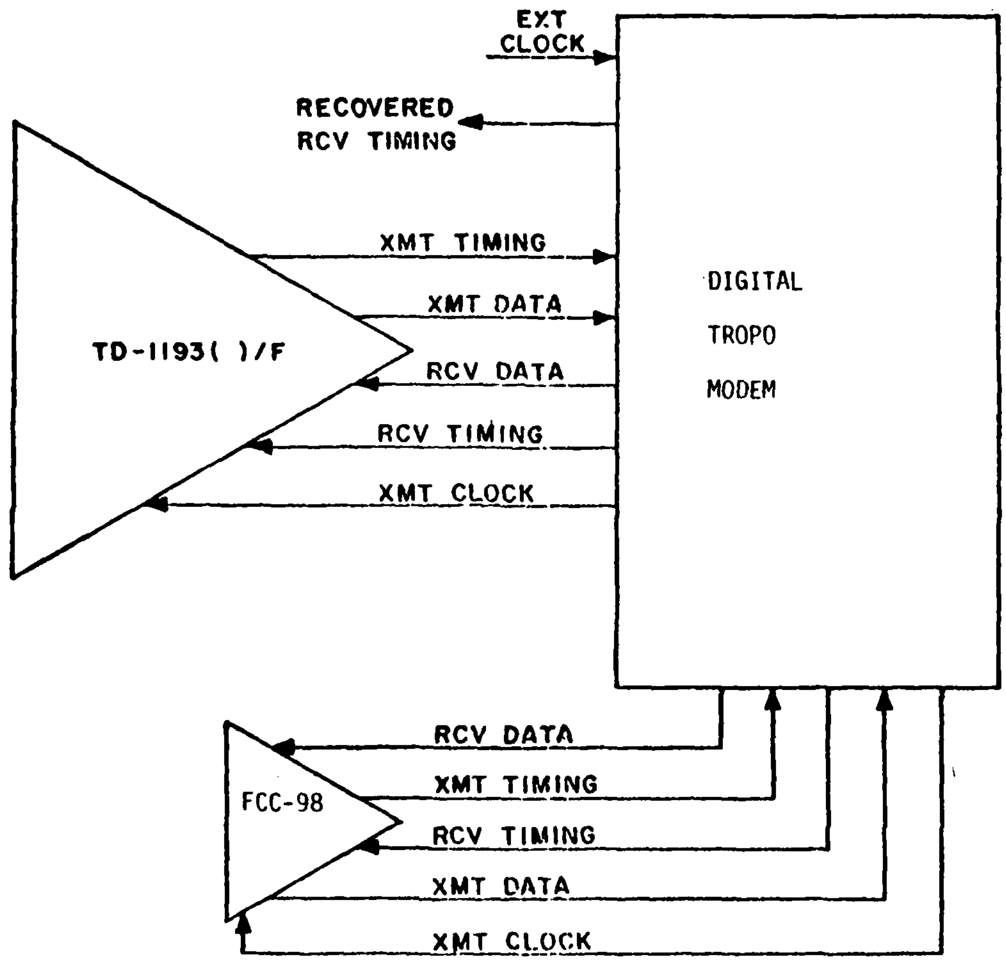


Figure B-2a. Modem Digital Inputs/Outputs

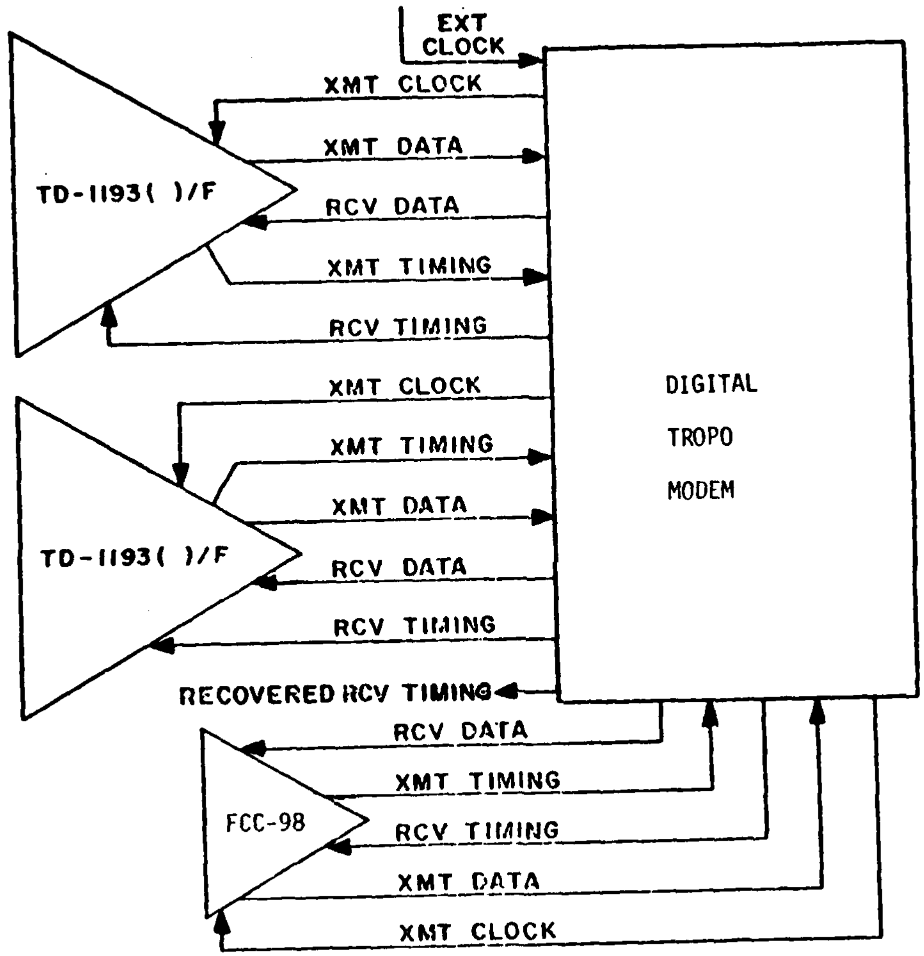


Figure B-2b. Modem Digital Inputs/Outputs

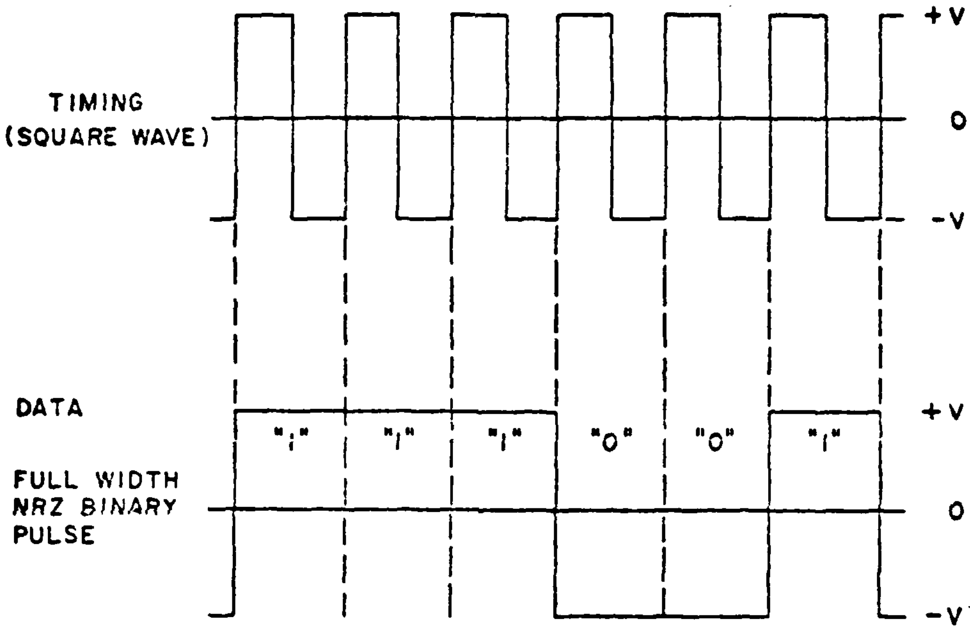


Figure B-3. Timing and NRZ Waveforms

3.2.1.3.3.2.2 Voltage Level. For the NRZ data and timing, a positive voltage is a logic one and a negative voltage is a logic zero. The open circuit voltage at the interface shall be plus or minus 4 volts, plus or minus 10 percent, and when terminated in its characteristic impedance, it shall be plus or minus 2 volts, plus or minus 10 percent.

3.2.1.3.3.2.3 Rise and Fall Time. The data and clock pulse output rise and fall times T_r and T_f, in Figure B-4, when measured between the 10 percent and 90 percent points shall be greater than 4 nanoseconds and less than 12 nanoseconds for data rates greater than 2 Mb/s, and shall be less than 100 nanoseconds for data rates 2 Mb/s or less.

3.2.1.3.3.2.4 Data/Timing Relationships. The trailing edge positive-to-negative transition of the output timing signal shall occur within plus or minus 4 percent of the center of the nominal unit interval of the output NRZ data signal, as shown in Figure B-5.

3.2.1.3.3.2.5 Output Jitter. The output data and timing signals shall not have more than plus or minus 4 percent jitter (peak-to-peak) of the nominal data unit interval.

3.2.1.3.3.3 Input Characteristics

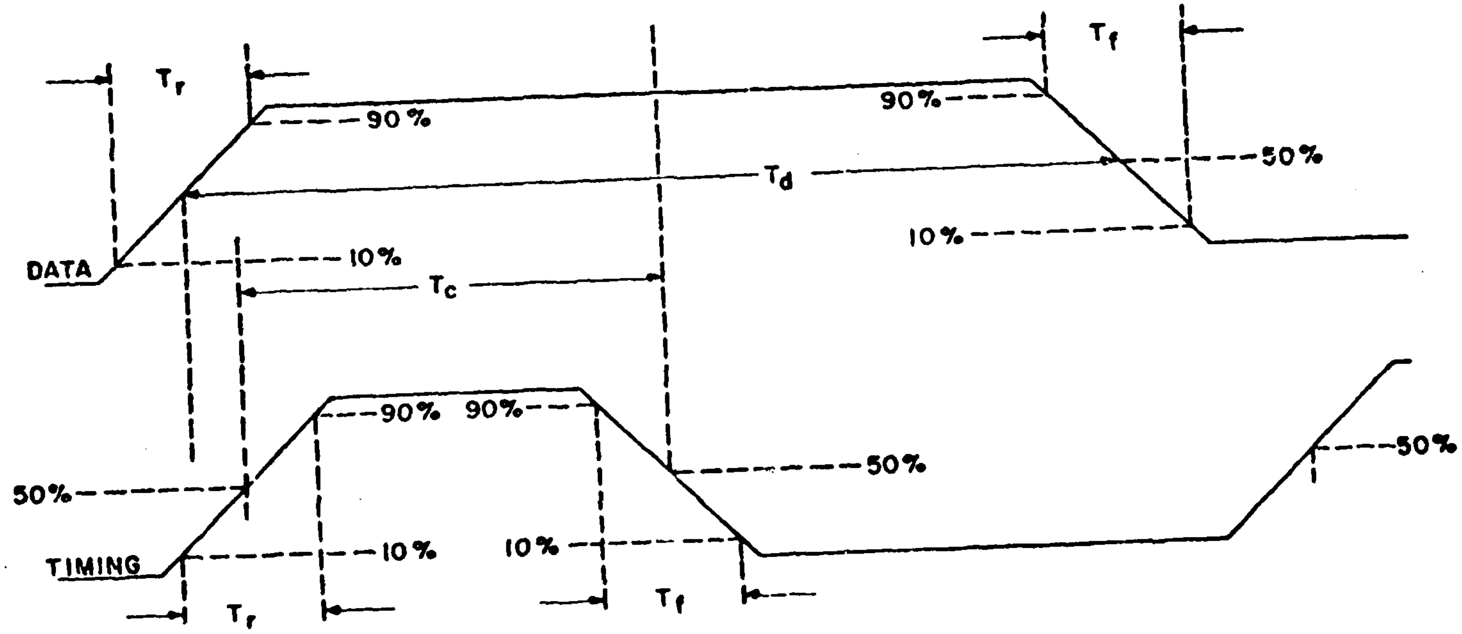
3.2.1.3.3.3.1 Impedance. The input cable termination shall be 78 ohms plus or minus 10 percent for NRZ data and timing inputs (balanced). The capacitive shunt shall be less than 15 picofarads to ground.

3.2.1.3.3.3.2 Voltage Level. At the digital inputs, a voltage level from plus or minus 0.2 volt to plus or minus 7.0 volts shall be correctly detected and processed without adjustment. Voltage levels up to and including plus or minus 14 volts shall not cause damage to the modem.

3.2.1.3.3.3.3 Sampling Interval. At the digital input, NRZ data and timing signals shall be detected and processed at the zero crossing of the positive-to-negative transition of the timing signal occurring within 25 percent of the center of the nominal data unit interval of the NRZ data as indicated in Figure B-6.

3.2.1.3.3.3.4 Combined Effects of Jitter. The modem shall operate properly with digital NRZ data and timing inputs, each having jitter equal to as much as 12.5 percent of data unit interval or a peak timing to peak data excursion of 25 percent of the data unit interval.

3.2.1.3.5 Mission Bit Stream (MBS) Rate. The modem shall accept the rates specified in Table B-III as input and provide these rates as output at the MBS inputs/outputs.



LEGEND:
T_d : NOMINAL DATA UNIT INTERVAL
T_c : NOMINAL TIMING INTERVAL
T_f : FALL TIME
T_r : RISE TIME

Figure B-4. Data/Timing Phase Relationships

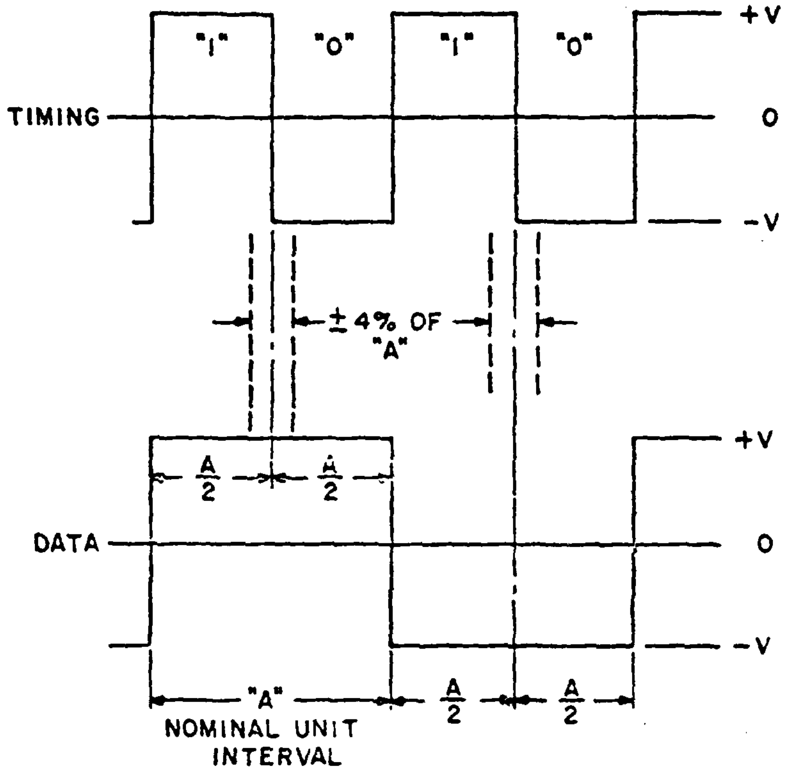


Figure B-5. Phasing (Data & Timing Relationships -- Trailing Edge)

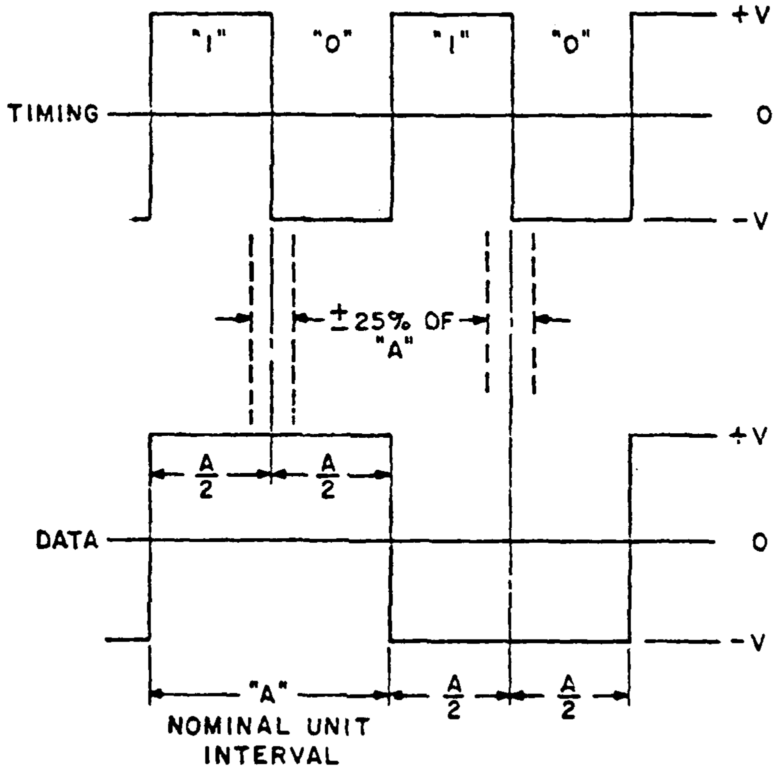


Figure B-6. Sample Interval (Data & Timing Relationships -- Trailing Edge)

3.2.1.3.6 Parallel Data. The modem shall provide and accept two synchronous MBS's at equal rates of 3.232 Mb/s and 6.464 Mb/s. These two data streams will be synchronously combined with the service channel bit stream.

TABLE B-III. MISSION BIT STREAM RATES

Nominal MBS Rate (Mb/s)	Nominal Data Unit Interval (msec)	Timing Frequency (MHz)
3.232	0.3094	3.232
6.464	0.1547	6.464
9.696	0.1031	9.696
12.928	0.0774	12.928

3.2.1.3.7 Service Channel Bit Stream (SCBS) Rate. The modem shall accept as input and provide as output an SCBS of nominally 192 kb/s. The SCBS operation will not be dependent on the presence of the MBS. The modem shall provide transmit clock and receive timing signals for the SCBS (see Figure B-2). The timing signals shall meet the input/output signal characteristics of 3.2.1.3.3.

3.2.1.3.8 Protection. The modem shall provide the following levels of protection.

3.2.1.3.8.1 Lockup Protection. The operation of the modem shall be such that when a 25 volt pulse as described below is applied simultaneously to any combination of input/output leads, no logic lockup shall occur that results in service outage or degraded performance requiring manual intervention to restore service. The rise time of the voltage pulse shall be 0.5 volts/ nanoseconds with a duration of 1 microsecond between the 50 percent amplitude points.

3.2.1.3.8.2 Interface Protection. Interface protection shall be provided to the extent specified in MIL-STD-188-100, paragraph 4.3.1.3.3.9, Protection, elements (a) through (d).

3.2.1.4 Internal Time Division Multiplex (TDM). For the purpose of multiplexing the one or two input mission bit streams and the SCBS, the radio shall contain a synchronous TDM.

3.2.1.4.1 Synchronization Acquisition Time. At a Mean E_b/N_o corresponding to a bit error rate of 1 part in 10(2), the modem internal TDM shall acquire synchronization 90 percent of the time within 50 milliseconds after application of the signal to the IF interface point (3.1.4).

3.2.1.4.2 Mean Time to Loss of Synchronization. At a mean E_b/N_o corresponding to a bit error rate of 1 part in 10(-2), the mean time to declaration of loss of synchronization of the modem internal TDM shall be not less than 24 hours. An external multiplexer frame search inhibit command signal shall be provided as an output of the modem. This signal shall inhibit the PCM and TDM multiplexer(s) interfaced with the modem from unnecessary reframe searches when either (a) the modem is in its frame reacquire (loss of BCI) mode, or (b) when the modem inhibits its own internal TDM frame search due to a low received S/N level (< 4 dB) or (c) when both conditions occur. The command signal shall be a transistor-transistor-logic (TTL) level available at a connector on the modem. The TTL signal shall be normally a logic one (high) when conditions a, b or c above are not present and shall be a logic zero (low) when conditions a, b or c are present, to inhibit multiplexer frame searches. The TTL command signal shall have a minimum fan-out capability for driving up to eight TTL loads.

3.2.1.4.3 Bit Count Integrity (BCI). The internal TDM shall detect a loss of BCI and reacquire synchronization within 50 milliseconds for 90 percent of the time at a mean E_b/N_o corresponding to a 10(-6) bit error rate, provided the receive data and TDM were within plus or minus 2 bits of synchronism.

3.2.1.5 Timing. The transmit clock shall be provided by an internal master oscillator providing performance as specified in 3.2.1.5.1, 3.2.1.5.2, and 3.2.1.5.3. In addition, the modem shall operate from an external source as specified in 3.2.1.5.4 and provide recovered receive timing as specified in 3.2.1.5.5.

3.2.1.5.1 Initial Accuracy. One hour after the modem is energized and at room ambient temperature (25°plus or minus 5° C), the frequency of the timing output shall be within plus or minus 3 parts in 10(6) of the nominal values specified in Table B-III.

3.2.1.5.2 Environmental Stability. The frequency of the timing output (Table B-III) of the internal TDM when subjected to the full operating temperature range specified in 3.3.10 shall not deviate more than plus or minus 10 parts in 10(6) at 25°plus or minus 5°C.

3.2.1.5.3 Long Term Stability. The frequency of the timing output (Table B III) of the internal TDM shall not deviate more than plus or minus 1 part in 10(6) per month when repeated readings are taken at any single stable temperature (within plus or minus 2° C) with the range of operating temperatures specified in 3.3.10.

3.2.1.5.4 External Clock Source. The modem shall also operate from an external clock source of 5 MHz. The timing signal shall be a SINUSOID wave at a level of OdBm + or - 3 dB. The stability and accuracy of the external clock source shall be + or - 1 part in 10^8. In the event the external source is lost, the modem shall automatically switch to the internal oscillator.

3.2.1.5.5 Receive Timing Output. Provisions shall be included in the modem to provide recovered receive timing as an output through a connector and shall meet the square wave timing requirements of 3.2.1.3.

3.2.2 Modulation Function

3.2.2.1 Transmitted Bandwidth Efficiency. When configured with any of the troposcatter radios listed in 3.2.1.3.1, the modem shall enable the transmitted bandwidth requirements as stated in 3.2.1.2 of this specification to be met at the radio/antenna interface for each data rate/bandwidth combination specified therein. The attenuation of the transmitted spectrum relative to its maximum value measured in a 4 kHz band shall not be less than that given by the following relationship:

$$A = 35 + 0.8\ (p-50) + 10 \log B$$

where: A = attenuation in decibels below spectrum maxima.
P = percent of transmitted bandwidth removed from the authorized frequency.
B = transmitted bandwidth in MHz.

3.2.2.2 Randomizing the Radiated Signal. The modulator function shall provide for the randomizing of the transmitted spectrum to reduce the intensity of discrete spectral components in the transmitted spectrum. The randomizer shall be of the self synchronizing type, contain a minimum of 20 stages, and shall meet performance requirements specified in Table B-IV. A strapping feature shall be provided to bypass the randomizer.

3.2.3 Demodulation Function

3.2.3.1 Modem Small Signal Performance. As a minimum, the modem shall provide the dual and quad diversity small signal performance stated in Table B-IV at the specified performance levels, for the MBS rate/transmitted bandwidth combinations delineated in paragraph 3.2.1.2 of this specification at rms fade rates of 0.01 to 10 Hz, inclusive.

TABLE B-IV. MODEM SMALL SIGNAL PERFORMANCE

Performance Level	Maximum Mean E_b/N_o for Profile P1		P2		P3		P4	
I	2.0	20.5	1.5	18.0	1.5	18.5	2.0	18.5
II	3.5	21.0	3.0	19.5	3.0	20.5	3.0	20.0
BER*	3E(-2)	3E(-8)	3E(-2)	3E(-8)	3E(-2)	3E(-8)	3E(-2)	3E(-8)

(a) Quad Diversity

Performance Level	Maximum Mean E /N for Profile P1		P2		P3		P4	
I	7.0	26.0	6.0	22.0	6.0	20.0	7.0	18.0
II	10.0	28.0	9.0	26.0	9.0	24.0	9.0	25.0
BER*	3E(-2)	3E(-8)	3E(-2)	3E(-8)	3E(-2)	3E(-8)	3E(-2)	3E(-8)

(b) Dual Diversity

* with randomizer (3.2.2.2)

3.2.3.2 Radio Degradation. When configured with any of the radios listed in 3.2.1.3.1, the performance provided by the modem shall not be degraded beyond 2 dB from the values listed in Table B-IV when the radios are operated at their maximum attainable output RF power.

3.2.3.3 Aircraft Fading. The modem shall suffer no transient or steady state degradation in performance when exposed to rapid fading characteristic or aircraft reflections in the vicinity of the transhorizon propagation path.

3.2.3.4 Modem Dynamic Range. The modem dynamic range is the difference in dB between the mean E_b/N_o determined in 3.2.3.1 above for a quad diversity 3 x 10(-8) BER and mean E_b/N_o above the level where the quad diversity BER becomes degraded from 3 x 10(-8). This dynamic range shall be a minimum of 50 dB for all profiles of Table B-I.

3.2.3.5 Modem BER Performance Floor. For a mean E_b/N_o 20 dB above the E_b/N_o values determined in 3.2.3.1 for quad diversity, the BER shall not exceed 1 error in 10(9) bits 95 percent of the time.

3.2.3.6 Frequency Stability. The modem 70 MHz local oscillator frequency shall remain constant within 5 parts in 10(6) over any 60-day period. This requirement shall be met beginning within 1 hour of the initial application of power under all operating and environmental conditions specified herein.

3.2.3.7 Intermodulation. With any two equal level signals outside the authorized bandwidth applied to the modem IF interface point (3.1.4) at a level of -40 dBm, the level of third order intermodulation products in the IF at a fixed gain shall not exceed the signal level in the IF that would result from a single in-band -90 dBm signal applied to the IF interface point (3.1.4).

3.2.3.8 Adjacent (Non-Contiguous) Channel Interference. The modem shall meet performance requirements specified herein with an interfering signal applied to the IF interface point (3.1.4) 50 dB above the desired signal at a frequency separation of twice the authorized bandwidth (Table B-II) or greater from the assigned frequency.

3.2.3.9 Co-channel Interference. The modem shall provide the performance specified in Table B-IV with less than 2 dB degradation receiver threshold, for interference of any type within the specified modem passband having the following levels with respect to the desired signal:

a. Minus 20 dB for performance Level I.
b. Minus 25 dB for performance Level II.

3.2.3.10 Carrier and Clock Recovery. The modem, when operating in quad diversity at a mean E_b/N_o corresponding to a BER of 1 error in 10(2) bits, shall provide carrier and clock-recovery within 1.0 millisecond. Once carrier recovery and bit synchronization have been achieved, BCI and bit synchronization shall be maintained for not less than one minute when the input mean E_b/N_o is reduced by 25 dB below the mean E_b/N_o specified in 3.2.3.1 for a BER of 3 parts in 10(8).

3.2.3.11 Spurious Response and Image Rejection. The modem IF input circuit selectivity characteristics from the combination of filters and tuned circuits shall be such that all signals which are at or greater than 70 MHz away from the IF center frequency shall be down more than 80 dB with respect to the desired signal frequency as measured at the output of the IF.

3.2.4 Monitoring and Alarm (Visible and Remote). The modem shall include circuitry to monitor functions and provide an alarm in the event of any failure listed below as a minimum. The alarm function shall include: (1) 1 amp contact closures (form C) for remoting to external alarm monitoring circuitry and, (2) illumination of visible alarm indicator on the front of the equipment for each failure. The following functions shall be monitored and alarmed.

3.2.4.1 Data Timing Input/Output. All inputs and outputs shall be monitored for loss of data or timing (3.2.1.3.2) (no transitions for 10 msec or more.) The alarm for one MBS or timing input/output shall be disabled when only one MBS or timing input/output is being used.

3.2.4.2 Modulator Output. Each modulator shall be monitored for loss of data activity (no transitions for 10 msec or more) and power.

3.2.4.3 Demodulator Output. Each demodulator output shall be monitored for loss of activity (no transitions for 10 msec or more).

3.2.4.4 Modem Frame. The internal TDM function shall be monitored for loss of receive frame synchronization.

3.2.4.5 Modulator Frequency Drift. An alarm indication shall be produced by the modem whenever the average transmitted IF frequency deviates more than 2 percent of the transmitted bandwidth (3.2.1.2).

3.2.4.6 Power Supply. A visible indicator shall be provided to indicate that primary power has been applied. In the event primary power is lost or the protective device fails, the indicator shall be extinguished.

3.2.4.7 Modulator Output Power. Each modulator IF output shall be monitored for a decrease in IF output power of 3 dB or more relative to the selected output power between 0 and 20 dBm.

3.2.4.8 IF Level. An alarm shall be provided which indicates that any diversity IF input is at or above the saturation level of the modem IF circuitry or below the minimum level required for satisfactory operation as defined in 3.2.3.1.

3.2.4.9 Frame Error Threshold. An alarm shall be provided which indicates when the error rate of framing bits exceeds 1 error in 10(4) Bits.

3.2.5 Performance Monitors. Test points shall be provided at the interface terminals for monitoring the following.

3.2.5.1 IF Received Signal Level. A signal shall be provided which is linearly proportional to the RSL measured at the IF interface in dBm. The monitor shall have a linear (+3 dB) range from 1 dB below to 50 dB above the RSL derived in 3.2.3.1 for the specified bit rates. The sensitivity shall be at least 0.1 volt per dB change in RSL.

3.2.5.2 Frame Bit Error Rate. The framing bits in the modem shall be monitored for errors. A pulse shall be provided at a connector on the modem when one or more frame errors occur. The source impedance shall be 75 ohms plus or minus 10 percent, unbalanced. The signal shall be 1 volt plus or minus 10 percent square pulses with nominal pulse duration equal to the data unit interval of the aggregate rate.

3.2.5.3 Signal Quality Monitor. The modem shall monitor degradation of the received demodulated signal (eye pattern) prior to data recovery and shall have an output voltage that is monotonically related to the signal-to-noise ratio of the demodulated signal. This relationship shall hold for a mean E_b/N_o of 20 dB to the mean E_b/N_o corresponding to a BER of 1 x 10(-1). In addition to the signal quality monitor output, buffered outputs shall be provided for each of the individual eye patterns.

3.2.6 Mean Time Between Outage. The modem shall have a Mean Time Between Outage of 100,000 hours where an outage is defined as a reduction of performance to less than that required herein for dual diversity operation.

DISTRIBUTION LIST

STANDARD:

R100 - 2
R102/R103/R103R - 1
R102M - 1
R102T - 9 (8 for stock)
R104 - 1
R110 - 1
R123 - 1 (Library)
R124A - 1 (for Archives)

R200 - 25
R300 - 1
R400 - 1
R500 - 1
R700 - 1
R800 - 1
NCS-TS - 1
101A - 1
312 - 1

R102T - 12

DCA-EUR - 2 (Defense Communications Agency European Area
ATTN: Technical Director
APO New York 09131)

DCA-PAC - 3 (Commander
Defense Communications Agency Pacific Area
Wheeler AFB, HI 96854)

DCA SW PAC - 1 (Commander, DCA - Southwest Pacific Region
APO San Francisco 96274)

DCA NW PAC - 1 (Commander, DCA - Northwest Pacific Region
APO San Francisco 96328)

DCA KOREA - 1 (Chief, DCA - Korea Field Office
APO San Francisco 96301)

DCA-Okinawa - 1 (Chief, DCA - Okinawa Field Office
FPO Seattle 98773)

DCA-Guam - 1 (Chief, DCA - Guam Field Office
Box 141 NAVCAMS WESTPAC
FPO San Francisco 96630)

US NAV Shore EE PAC - 1 (U.S. Naval Shore Electronics Engineering
Activity Pacific, Box 130, ATTN: Code 420
Pearl Harbor, HI 96860)

1843 EE SQ - 1 (1843 EE Squadron, ATTN: EIEXM
Hickam AFB, HI 96853)

DCA FO ITALY - 1 (DCA Field Office Italy, Box 166
AFSOUTH (NATO), FPO New York 09524

DISTRIBUTION LIST (cont'd)

USDCFO - 1 (Unclassified/Unlimited Distribution)
(Chief, USDCFO/US NATO
APO New York 90667)

SPECIAL:

DCA - 1 Code 470
DCA - 1 Code 513

DCA Athens - 1 (Chief, DCA Field Office Athens
APO New York 09223)

HQ USAF
ATTN: RDSS
Washington, DC 20330

Commander, USAF Europe
ATTN: DCR
DCO
DOY
LG
APO New York 09633

Commander
Rome Air Development Center
ATTN: DCC
Griffiss AFB, NY 13442

Commander
Electronic Systems Division (AFSC)
ATTN: DCF-1
DCJ
WE
Hanscom Field, MA 01730

Commander
Air Force Communications Command
ATTN: EPPD
LGMKR
1842EEG
Scott AFB, IL 62225

Commander, NCA
ATTN: EIEGM
Griffiss AFB, NY 13442

Commander in Chief
European Command
ATTN: ECJ-6
PP
PF
APO New York 09128

Commander, ADCOM
ATTN: XP
Peterson AFB, CO 80914

Commander
European Communications Area (AFCC)
ATTN: LGM
APO New York 09633

Commander
Sacramento Air Logistics Center
ATTN: MMCREA/Mr. J. Flatt
Sacramento, CA 95652

Commander, USACSA
ATTN: CCM-RD
CCM-TS-C
Ft. Monmouth, NJ 07703

Commander, USACC
ATTN: CC-OPS-SR
CC-OPS-ST
Ft. Huachuca, AZ 85613

Commander, USACEEIA
ATTN: CCC-CED-XEM
Ft. Huachuca, AZ 85613

Commander, USACORADCOM
ATTN: DRDCO-COM-RM-3
Ft. Monmouth, NJ 07703

Commander
Naval Telecommunications Command
ATTN: Code 621A
4401 Massachusetts Avenue
Washington, DC 20390

National Security Agency
ATTN: S03
Ft. Meade, MD 20755

Director
Joint Tactical Communications
ATTN: TT-E-EX (TRI-TAC) Office
Ft. Monmouth, NJ 07703

U.S. Department of Commerce
Institute for Telecommunications Science
ATTN: Mr. W. Hubbard
Boulder, CO 80303

Electromagnetic Compatibility Analysis Center
North Severn
ATTN: CJ
Annapolis, MD 21402

DATE

FILMED